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F/FB-111 ESCAPE INJURY MECHANISM ASSESSMENT

LEON E. KAZARIAN

OCTOBER 1977

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AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

TECHNICAL REVIEW AND APPROVAL

AMRL-TR-77-60

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Henning E. von Gierke

HENNING E. VON GIERKE
Director
Biodynamics and Bionics Division
Aerospace Medical Research Laboratory

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

- **All F/FB-111 ejections, for the period October 1967 to June 1977, have been reviewed from an orthopedic biomechanical point of view.**
- **A suggested radiographic method for identifying and classifying the unique spinal injury patterns in the F/FB-111 is presented.**
- **A type of fracture due to hyperextension of the upper thoracic spine, previously unidentified in the clinical and operational environment and having clinically unfamiliar features, is described.**

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Block 20. Abstract (cont'd)

- F/FB-111 spinal injuries have been classed as (a) hyperextension injuries, (b) hyperflexion injuries, and (c) combination hyperextension/hyperflexion injuries. Hyperextension injuries are due to the direction of force application of the powered inertia reel, and they occur during the powered inertia reel retraction phase of the ejection sequence. Hyperflexion injuries are due to the ineffectiveness of the upper torso harness, and they occur following ground landing impact. Combination injuries (hyperextension/hyperflexion) are common.

- The mechanism of spinal injury in most aircrewmen is best understood and most often diagnosed by a combination of careful aircrew questioning, clinical history, and thorough roentgenographic assessment. The operational, clinical, and roentgenographic features should be complementary.

- A new technical order has been incorporated into the F/FB-111 emergency escape procedures. The severity and frequency of hyperflexion injuries have been reduced.

- The design deficiency in the configuration of the support and restraint system has been identified, with the result that corrective action has been initiated.

- Despite careful clinical and roentgenologic examinations, the true sequelae of even minor spinal trauma cannot be radiographically identified or clarified immediately following ejection injury. Only after long periods of observation with systematic serial roentgenographic examinations are the secondary sequelae recognized.

- The basic orthopedic biomechanical principles employed herein to uncover the mechanics and modes of operational spinal injuries should be applied to other operational weapon systems.

PREFACE

The preparation of this report involved the assistance of many people and organizations. Those to whom the author especially wishes to express his appreciation and thanks are:

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A very special thanks to the USAF F/FB-111 aircrewmen whose crew module ejection data were used as a basis for this study. It is anticipated that this information will help elucidate many of the problems during aircrew ejection, and hopefully will aid in establishing requirements for safer and more efficient life support and escape equipment standards for current and future weapons systems.

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INTRODUCTION

During the years 1970 to 1975, a larger than expected number of F/FB-111 aircrewmen, forced to use the crew escape module, suffered spinal injuries during otherwise uneventful ejections. This apparent adverse trend in the incidence and severity of F/FB-111 aircrew spinal injuries attracted considerable attention and stimulated intensive inquiry about the cause of the injuries in order to implement appropriate corrective measures. In response to the expressed concerns, an investigation was initiated to analyze the biodynamic pathogenetic mechanisms of spinal trauma associated with the F/FB-111 weapon system.

This report summarizes the findings of extensive clinical, radiographic, aircraft accident reports and orthopedic biomechanical investigations over the past two years (June 1975-June 1977) for use in assessing spinal injury patterns and their biomechanics in the F/FB-111 weapon system. The data presented herein are based upon systematic review of all F/FB-111 aircraft investigation reports, post-ejection radiographs, clinical records, and the elicitation of aircrewmen responses to the history and conditions of flight just before ejection initiation. Visits were made to several F/FB-111 bases; ejected and ejected-injured aircrewmen were interviewed; anthropometric data using the F/FB-111 simulator and F/FB-111 aircraft were amassed. Basic radiographic data on injured aircrewmen were supplemented by tomographic investigation. The factors accountable for the unique osseous vertebral lesions experienced by F/FB-111 aircrewmen are described and classified from an orthopedic biomechanical point of view. Spinal injury patterns are assessed and interpreted in terms of operational factors. Solutions to the back injury problem are recommended. Long term consequences of the spinal injuries on spinal morphology and kinesiology are described.

F/FB-111 EJECTION STATISTICS

During the period 19 October 1967 to 30 June 1977, the total number of F/FB-111 ejection attempts was 39, involving a total of 78 aircrewmen. Ejection attempts by year are shown in Figure 1. Of these 39 ejections:

16 aircrewmen (20.5%) were fatalities
25 aircrewmen (32.0%) sustained back injuries
2 aircrewmen (2.6%) sustained back strains
35 aircrewmen (44.9%) sustained no back injuries

Figure 2 presents the number of ejections by year versus injury distribution. The crewmen involved are identified. (There were no fatalities or serious injuries observed when ejection was initiated within the nominal ejection envelope and when full system sequencing occurred. All fatalities were the result of ejection initiation too late for full system sequencing to take place, or of ejection system component failure or malfunction interrupting normal sequencing.)

Removing the fatalities from the injury statistics:

25 aircrewmen (40.3%) sustained back injuries
2 aircrewmen (3.2%) sustained back strains
35 aircrewmen (56.5%) sustained no back injuries

The F/FB-111 back injury rate for successful ejections is currently 43.5%.

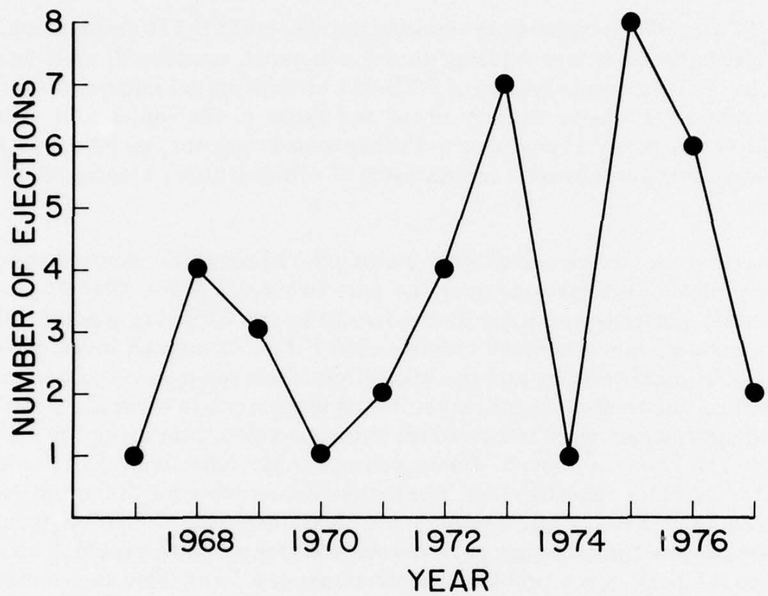


Figure 1. Number of Ejections From F/FB-111 Aircraft by Year

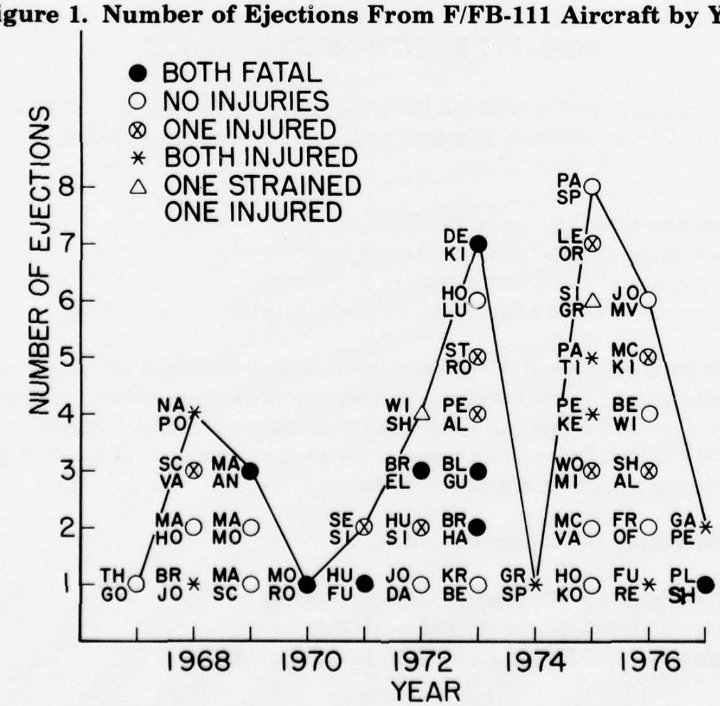
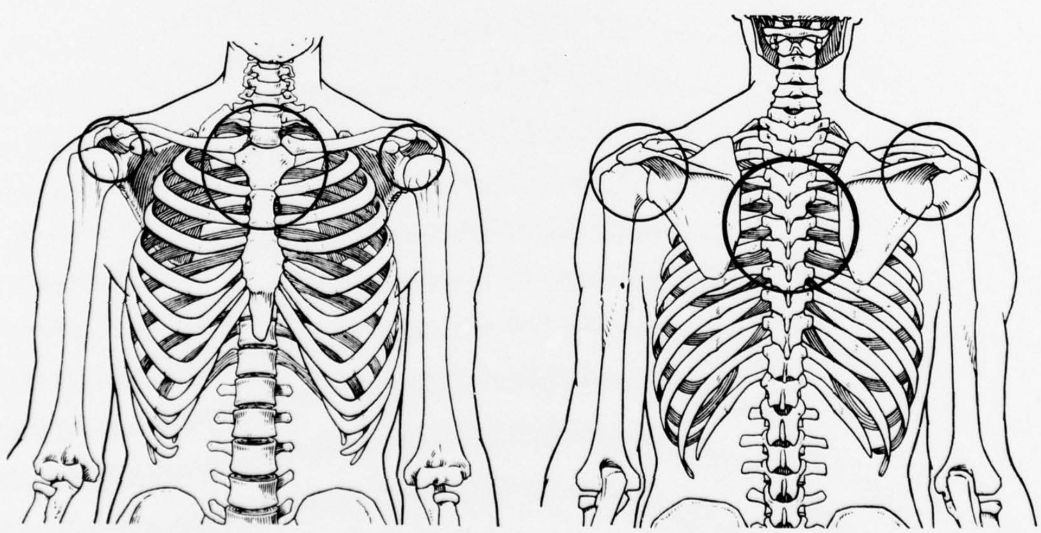


Figure 2. Number of F/FB-111 Ejections Versus Injury Profile by Year

CLINICAL FINDINGS

Based upon review of postejection clinical symptomatologies and radiographic analysis, accident investigation board findings, aircrew interviews, and secondary follow-up postejection investigations, clinical symptomatology repeatedly exhibited tenderness or pain in the anatomical areas circled in Figure 3. In almost all instances, during or immediately following ejection or ground landing impact, the injured aircrewman complained of a more or less discomforting to severe interscapular pain in the upper thoracic spinal region. On physical examination, the spinal region involved was considerably stiff and always corresponded to subjective symptoms. In a number of cases, inspection revealed paravertebral swelling around the fracture focus that was highly painful under palpatation or light percussion or both. In the more severe cases, breathing was shallow and deep breathing resulted in acute chest pain, which was partially aggravated by coughing or sneezing. Tenderness was usually present over the acromial ends of the clavicles and was also present over the acromial processes, just internal to the attachment of the coracoid ligament. Acromioclavicular separation could also be manifested. Separation at the junction of the manubrium with the gladiolus of the sternum was suspected in five aircrewmen.



Front of portion of skeleton showing thorax.

Back of portion of skeleton showing thorax.

Figure 3. Skeletal Sites of Common Clinical Symptomatology as a Result of F/FB-111 Ejection Forces With or Without Accompanying Spinal Trauma

RADIOGRAPHIC INTERPRETATIONS

Analysis of routine anterior-posterior and lateral roentgenograms revealed mild anterior wedge compression to be the most common form of fracture, as illustrated in Figure 4. Vertebral column splaying as shown in Figure 5 was occasionally observed. Fragmentation and/or separation of the anterior superior marginal ring of the vertebral body was occasionally suspected. Fractures seemed to be most prevalent in the mid-lower thoracic spinal column.

In reviewing all available roentgenograms at the respective F/FB-111 bases, many were found to be of poor quality. Fracture lines were not clear, and a majority of the spinal lesions were diagnosed by inference rather than positive radiographic findings. I decided that tomographs were required to further supplement and complement the radiographic data.

Tomography is a radiographic technique used for enhancing the detail of structures within a particular plane of tissue (in this case, the spinal column) while blurring the detail of structure below and above this focal plane. Multiple serial radiographic exposures were taken at different spinal planes and the lesions were reconstructed. An example of a routine radiograph versus a tomographic view of exactly the same vertebral level is shown in Figure 6 A and B. The arrow on the tomogram identifies a spinal injury, which cannot be recognized on the routine radiographs. Common patterns of spinal injury seen from the tomographic analysis are illustrated in Figures 7 to 11.

Figure 4. Lateral View of Upper Thoracic Spine
[Mild Anterior Wedge Compression Fractures (Arrow)]

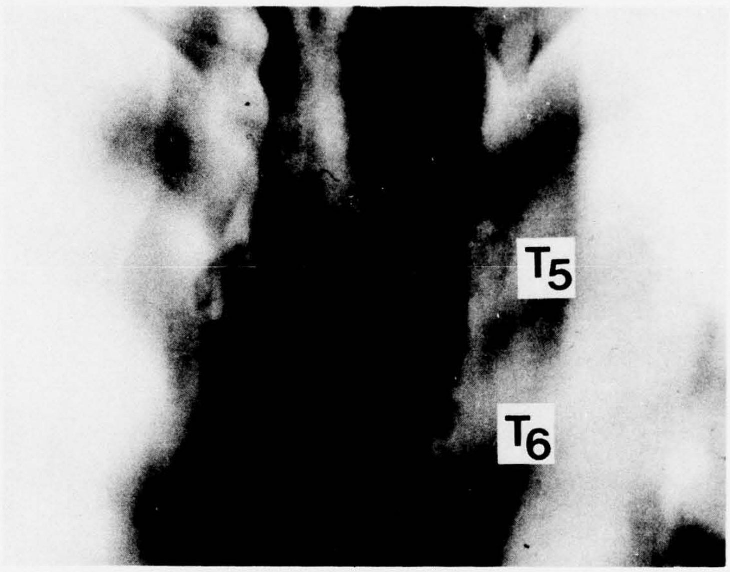


Figure 5. Anterior/Posterior View of Upper Thoracic Spine Showing A Splaying Fracture at T_5 With Scoliosis

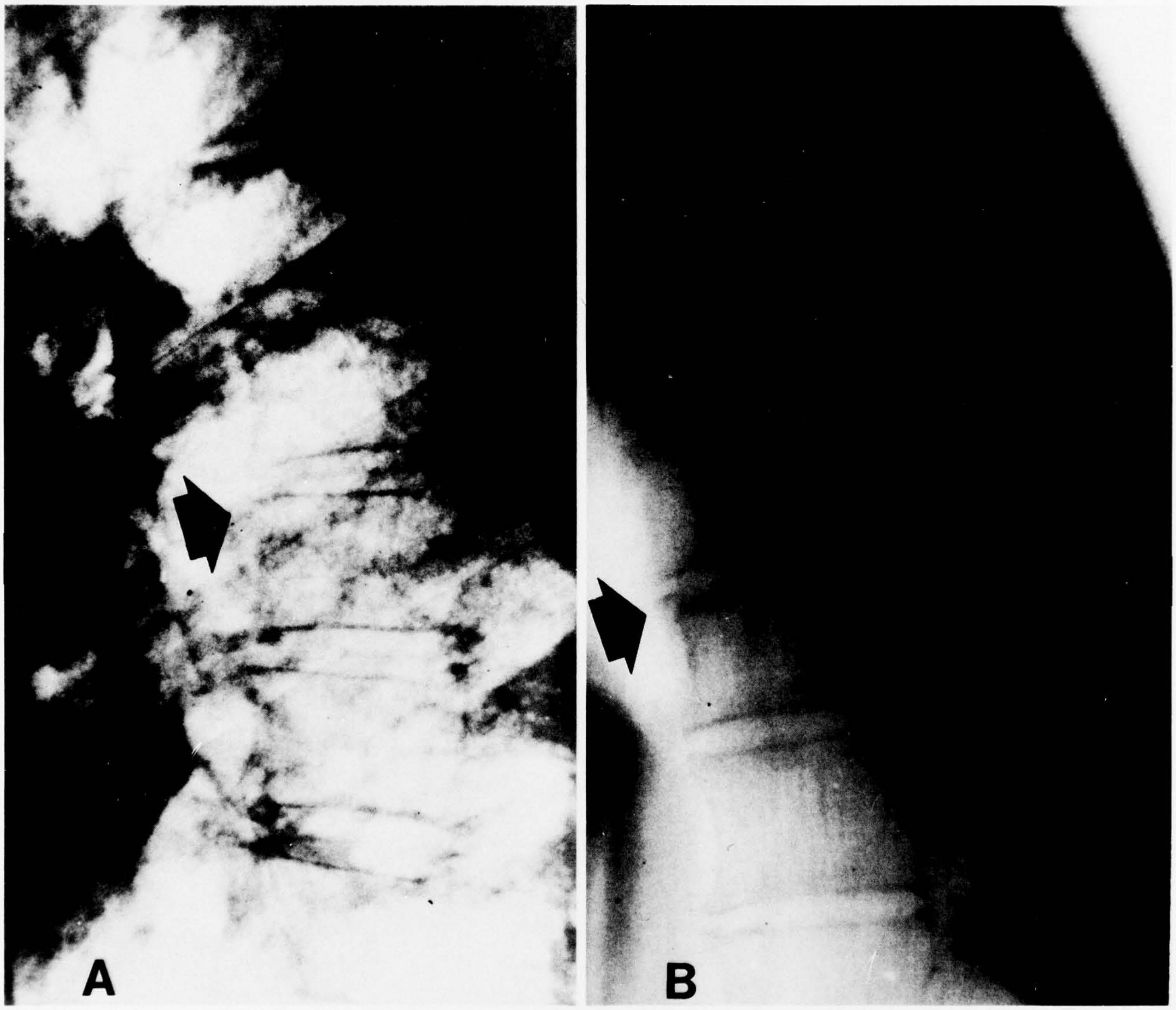


Figure 6. Example of a Routine Radiograph (A) Versus Tomographic View (B) [The Injury Identified by the Arrow in the Tomograph is Not Apparent on the Routine Radiograph]

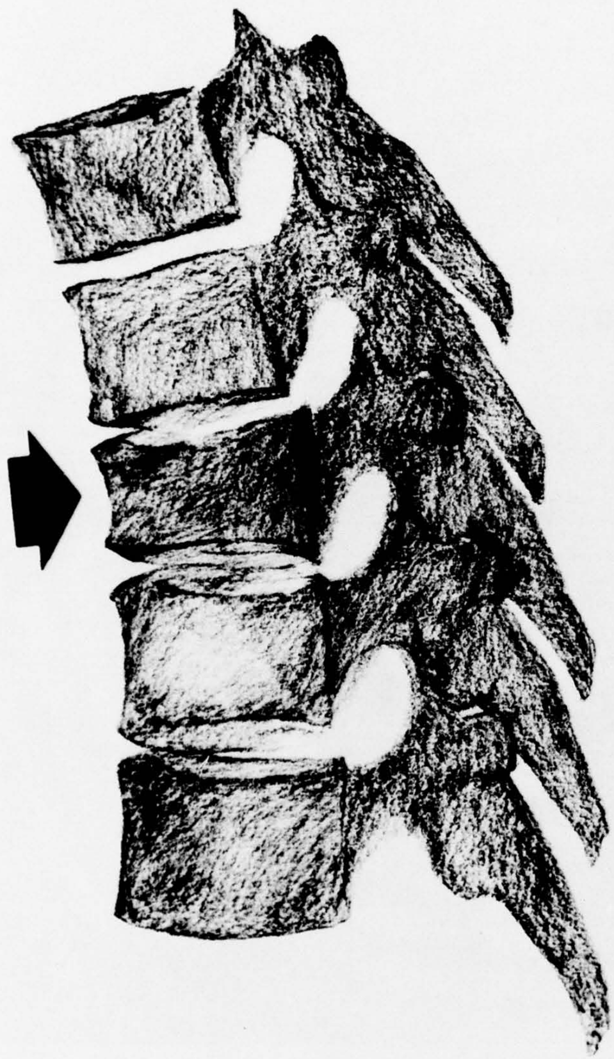


Figure 7. Lateral View of Upper Thoracic Spine Illustrates a Loss in Continuity of the Posterior Vertebral Centrum Curvature and a Mild (< 10%) Loss in Vertebral Centrum Height (Arrow)

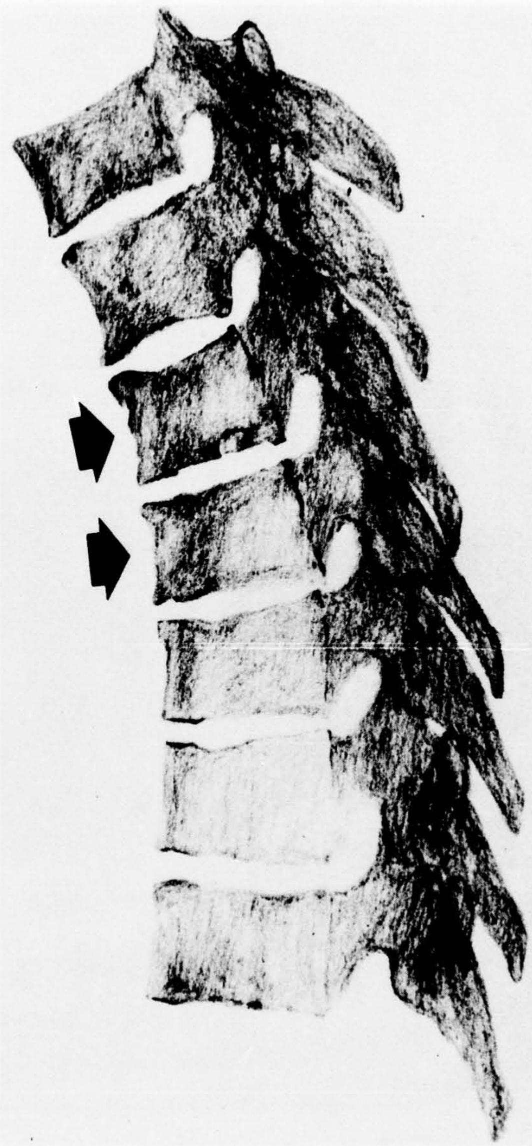


Figure 8. Lateral View of Upper Thoracic Spine Illustrates Anterior Wedge Compression Fracture (Arrows), With Approximation of Posterior Vertebral Centrum Height

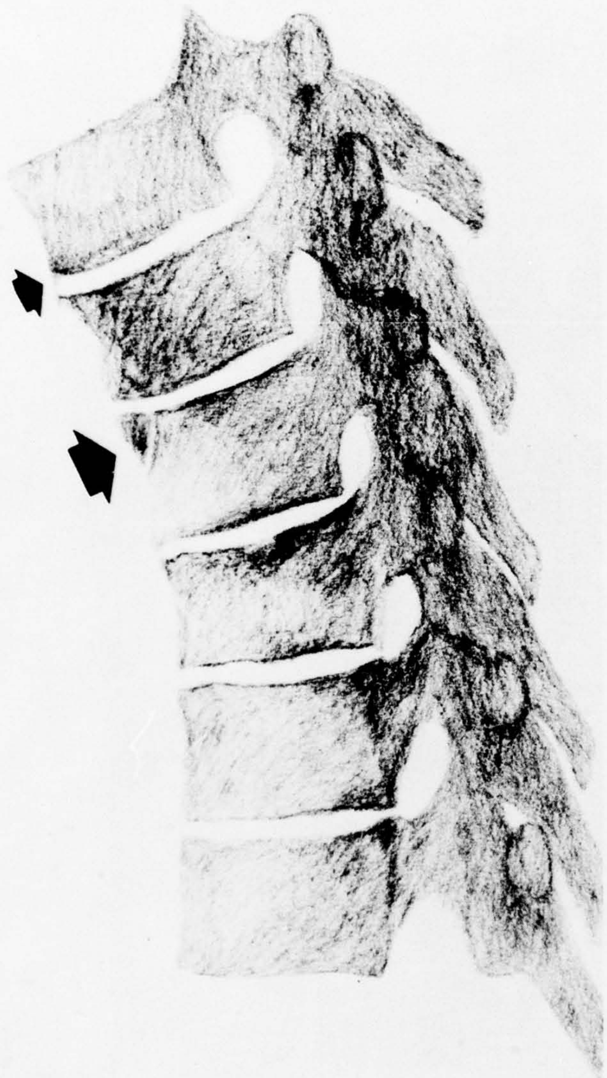


Figure 9. Lateral View of the Upper Thoracic Spine Illustrates Loss in Anterior Vertebral Centrum Height at T_6 [Disruption of the Anterior Superior Marginal Ring at the T_4-T_5 Level (Arrows)]

Figure 10. Lateral View of the Upper Thoracic Spine Illustrates Loss in Anterior Vertebral Centrum Height at Two Levels [Disruption of the Anterior Superior Marginal Ring at T_6 and T_7 (Arrows)]

Figure 11. Lateral View of Upper Thoracic Spine Illustrates:
(1) Disruption of the Posterior Vertebral Body Height and Continuity at T_5 and T_6 (Top Arrow)
(2) Avulsion Fracture at T_6 (Bottom Arrow)

LEVEL AND DISTRIBUTION OF SPINAL INJURY IN THE F/FB-111 CREW ESCAPE MODULE

Based on tomographic interpretations, the distribution of spinal trauma as a function of spinal level for the F/FB-111 crew escape module is shown in Figure 12. The most frequently affected vertebral levels involved are those of the 4th, 5th, 6th, and 7th thoracic vertebrae, with a well defined prominence at the level of the 5th and 6th thoracic vertebrae. Figure 13 illustrates the human spinal column and identifies the region of spinal injury in the F/FB-111.

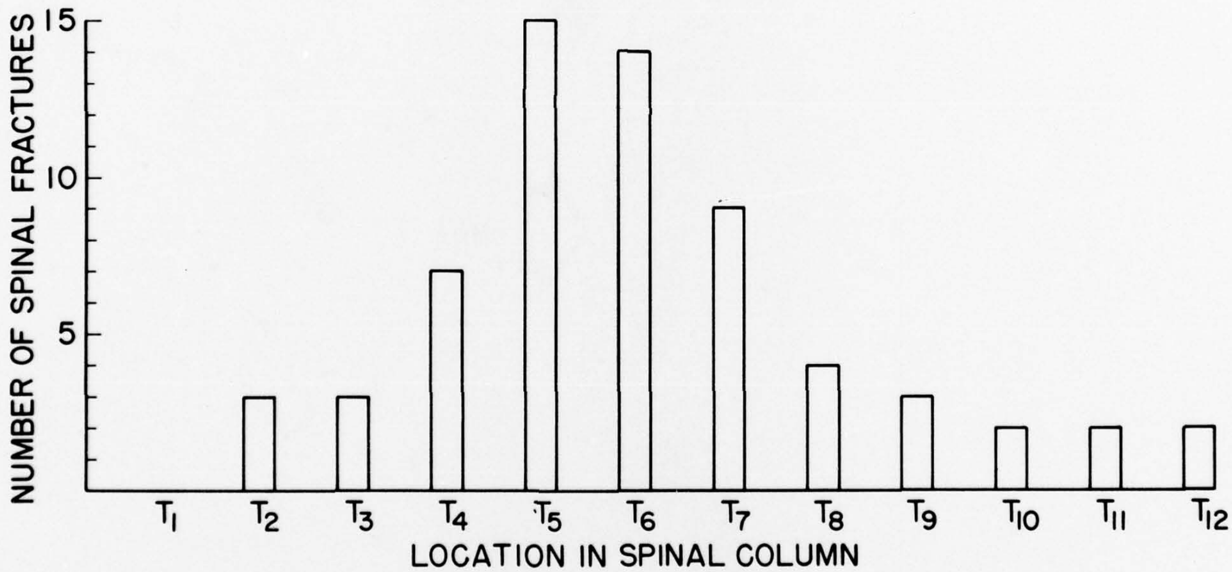


Figure 12. Spinal Fracture Frequency According to Location in Spinal Column

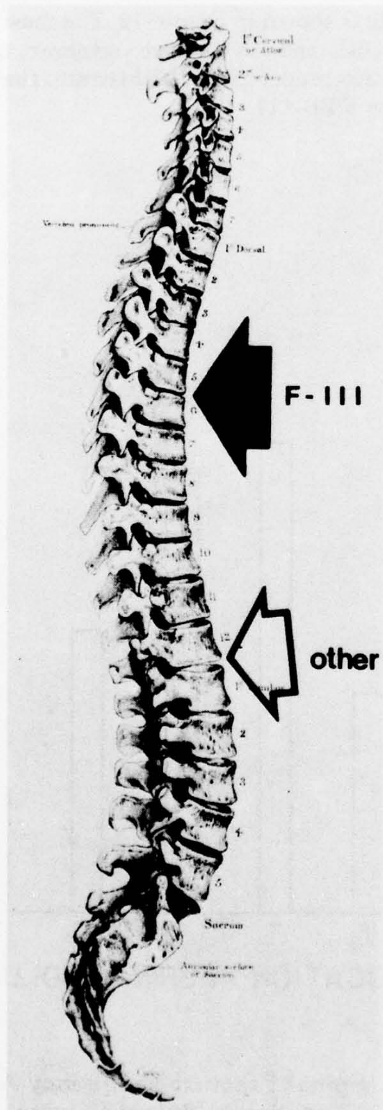


**Figure 13. The Human Spinal Column:
A Comparison of Injury Levels Between F/FB-111 Ejections
(Solid Black Arrow) and Routine Open Seat Ejections (Other Arrow)**

CLASSIFICATION OF VERTEBRAL CENTRUM INJURIES

All vertebral fracture patterns were roentgenographically characterized by the fracture or callus lines of fracture fragments and by displacement of fracture fragments. These were then classified on an anatomical, kinesiological and pathological basis under the following headings:

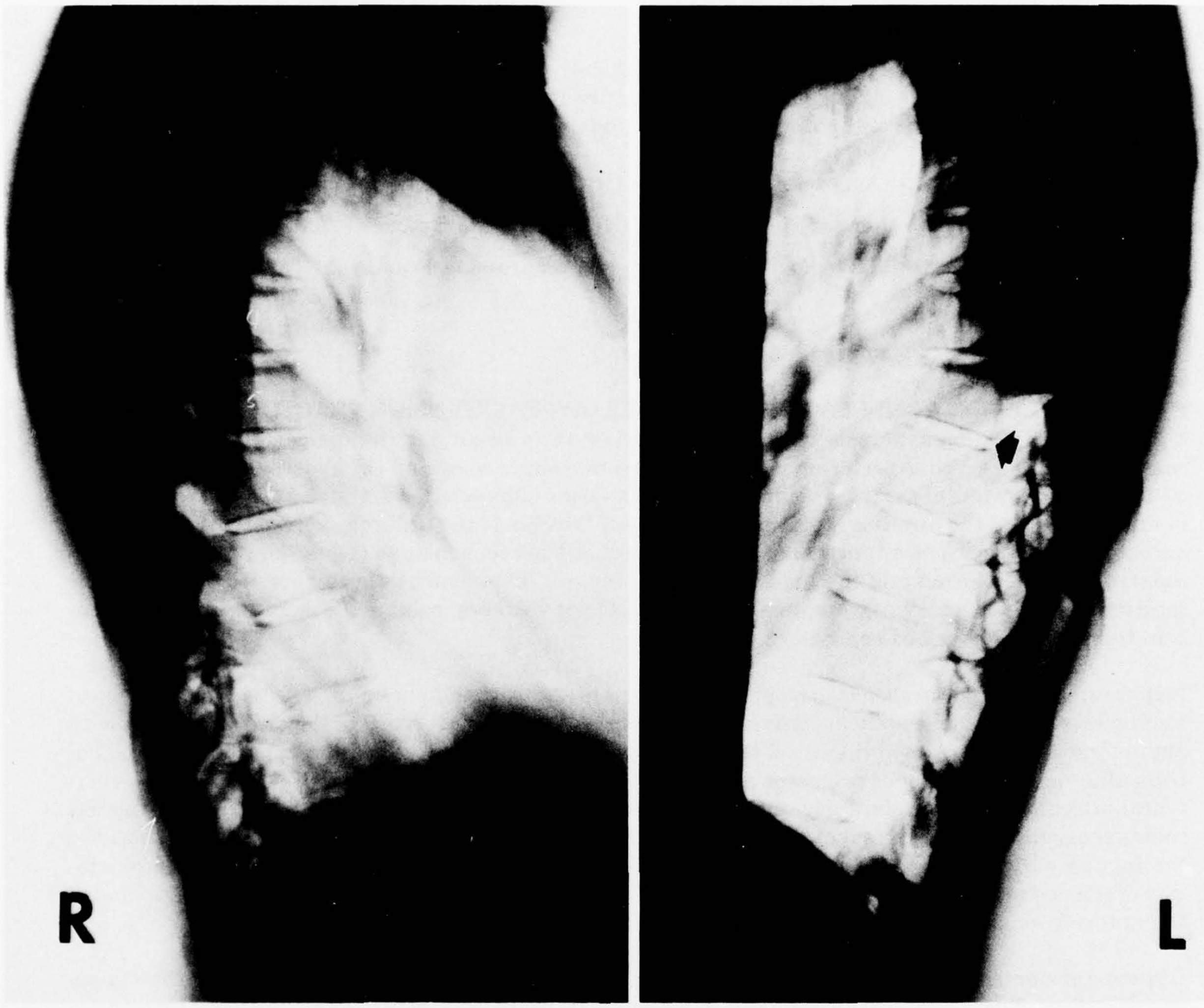
- Posterior Height Compression Fractures (Hyperextension Fractures)
- Anterior Wedge Compression Fractures (Hyperflexion Fractures)
- Combined Anterior Wedge/Posterior Height Compression Fractures
- Burst Injuries
- Lateral Wedge Compression Fractures

POSTERIOR HEIGHT COMPRESSION FRACTURES (HYPEREXTENSION FRACTURES)

Upper thoracic column hyperextension fractures fall into two dissimilar anatomical forms: (1) hyperextension fractures *without* posterior vertebral centrum compression and (2) hyperextension fractures *with* posterior vertebral centrum compression. Both forms of hyperextension fracture may or may not result in injury to the anterior longitudinal ligament that binds the different vertebrae together. The extent of injury varies as a function of one or more of at least four factors: (1) vertebral body displacement, (2) degree of arcing of the upper thoracic spine, (3) involvement of the anterior aspects of the intervertebral disk, and/or (4) compression of the posterior vertebral column. Both forms of hyperextension fracture are described separately.

Hyperextension fractures *without* posterior vertebral body compression, studied by means of roentgenographic/biomechanical analysis, divulged a reduction in intervertebral disk space height with approximation and/or bony bridging of the vertebral body with a slight deviation in posterior vertebral body alignment. The spinous processes are usually in proximity. The intervertebral disk and intervertebral articulations often show asymmetries, broadening or narrowing. Figure 14A is a right and left roentgenogram depicting an asymmetric vertebral centrum approximation. Figure 14B accentuates the findings on radiograph 14A. Figure 15 is a lateral illustration of the thoracic spine showing approximation of the posterior vertebral body borders at two vertebral levels (arrows) with minimal disruption of the anterior longitudinal ligament from the anterior-superior marginal ring.

Hyperextension fractures *with* posterior vertebral centrum compression present different roentgenographic signs. Roentgenographic/biomechanical analysis revealed a reduction in posterior intervertebral disk space height with approximation and/or crushing of posterior vertebral body height. There is also compression trauma to articular facets, pedicles and/or laminae. This fracture mode is unstable, that is to say, some neurological damage may have occurred that can be related to the bony injury, and that this relationship has a definite place in the initial diagnosis of the mechanism of injury. Some of the pathological findings that could be identified on lateral roentgenograms included divergence of bony axis of the spinous process at the precise level of injury, marked decrease in intervertebral disk space height, and undulating bony bridging of the posterior vertebral body heights. Comparative posterior vertebral centrum continuity may diverge and become irregular as illustrated in Figure 16. The internal architecture of the vertebral centrum may lose its homogeneity, and there may be an increase in the internal density of trabecular bone in the posterior third of the vertebral centrum. The anterior superior margin of the involved vertebra is often mottled and irregular, the width of the line is irregular, and the margins of the line, angular. A portion of the ring apophysis may be elevated from the centrum by avulsion with respect to the location of the fulcrum of action tearing the anterior longitudinal ligament. Figure 17 is a lateral view of the thoracic spine showing avulsion of the anterior longitudinal ligament at two vertebral levels. Eighteen aircrewmen have sustained hyperextension spinal injuries.



14A

Figure 14A. Radiographs of Right and Left Lateral View of the Upper Thoracic Spine Revealing Asymmetrical Approximation of Posterior Vertebral Centrum Heights at the Level of T_4–T_5–T_6–T_7

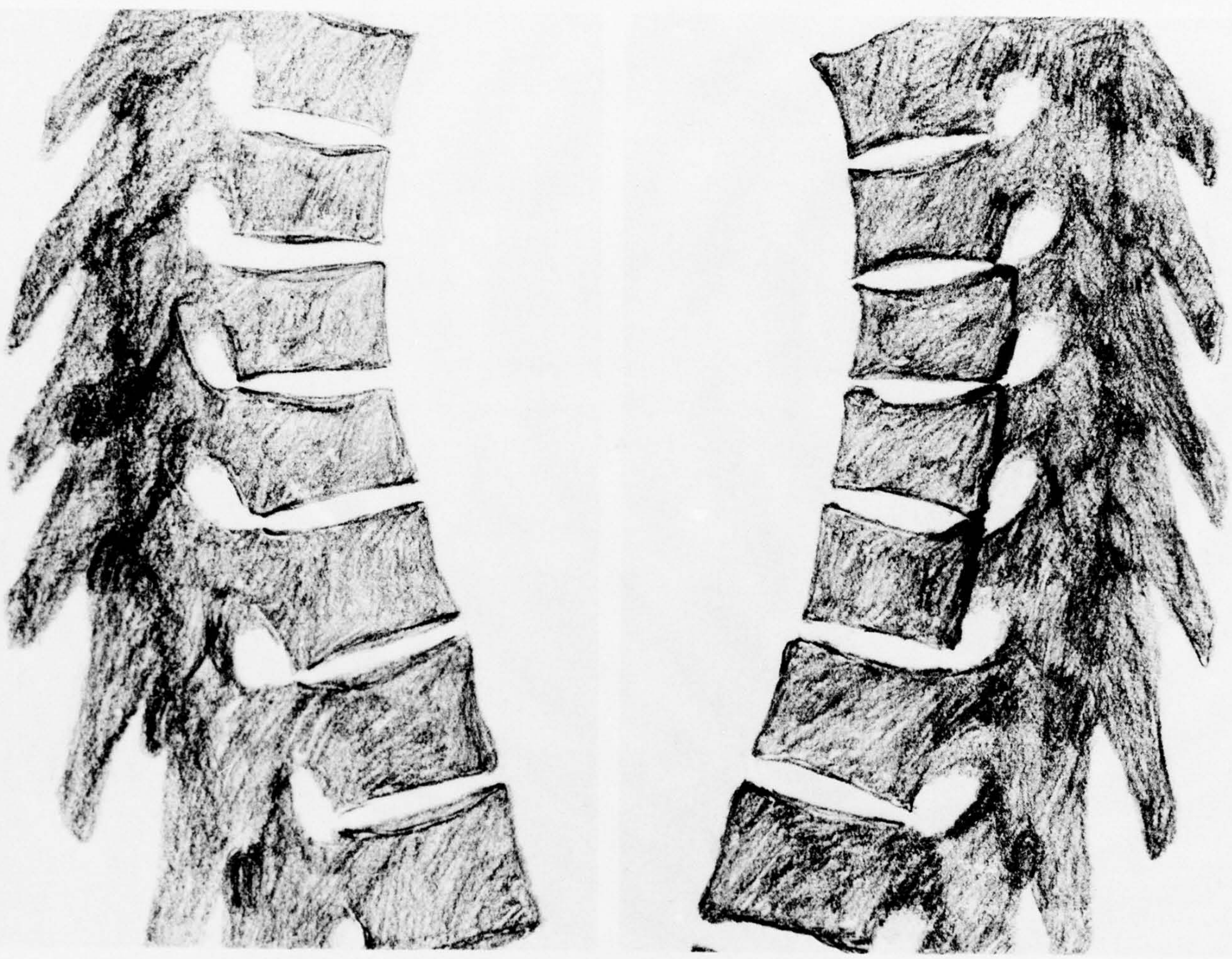


Figure 14B. Schematic of Figure 14A

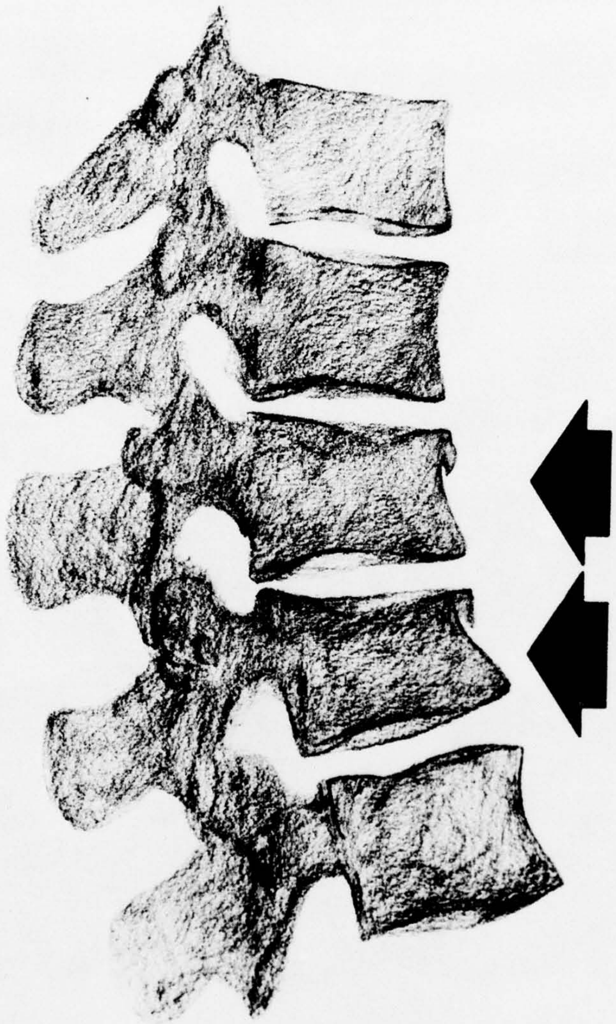


Figure 15. Lateral View of the Upper Thoracic Spine Illustrates Asymmetrical Vertebral Centrum Approximation with Minimal Avulsion of Anterior Longitudinal Ligament (Arrows)

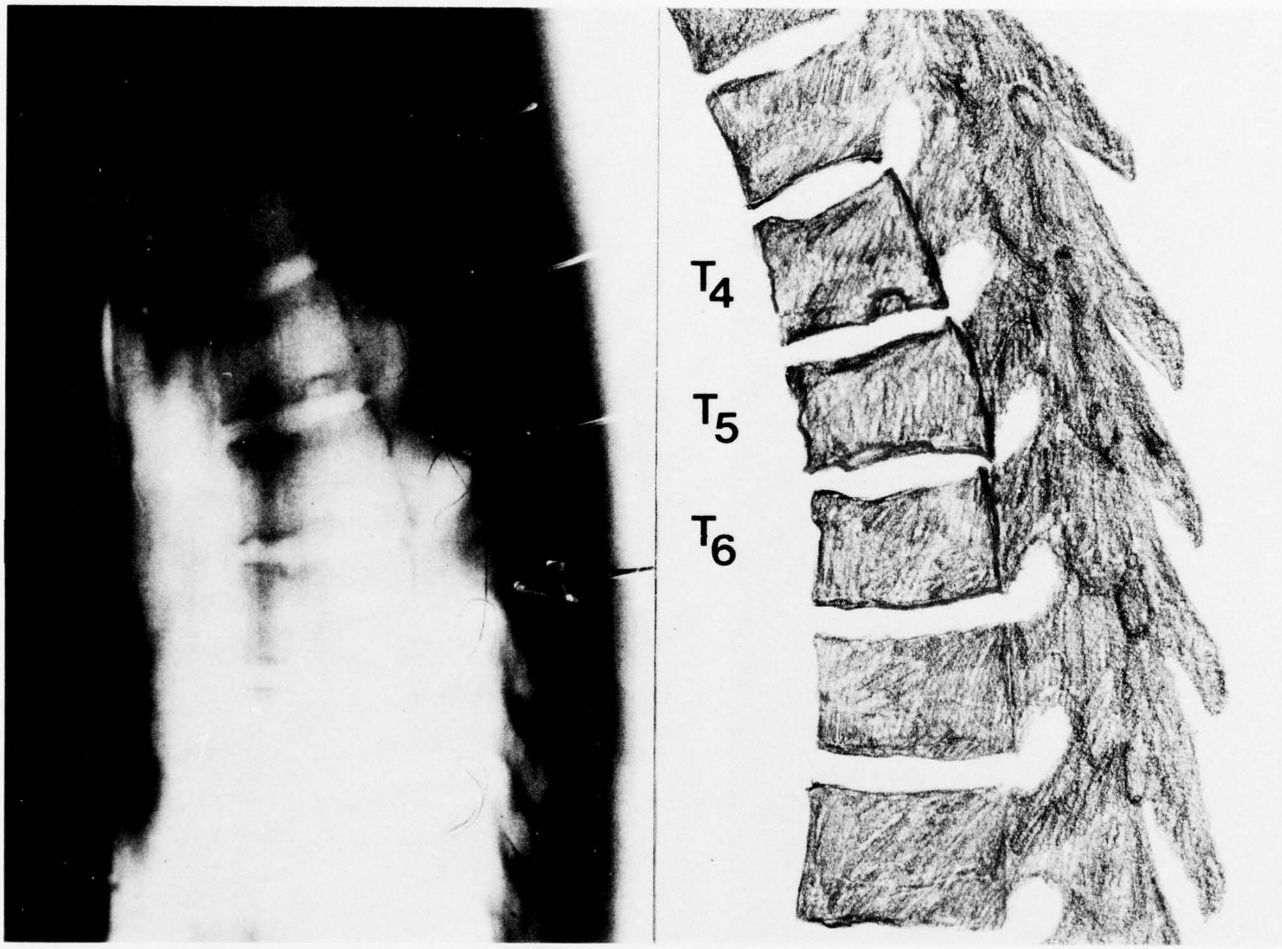


Figure 16. Lateral View of Upper Thoracic Spine Illustrates Narrowing of Intervertebral Disk Space Heights at the T_4–T_5–T_6 Levels With Bony Bridging or Contact of Posterior Adjacent Vertebral Centrum Heights

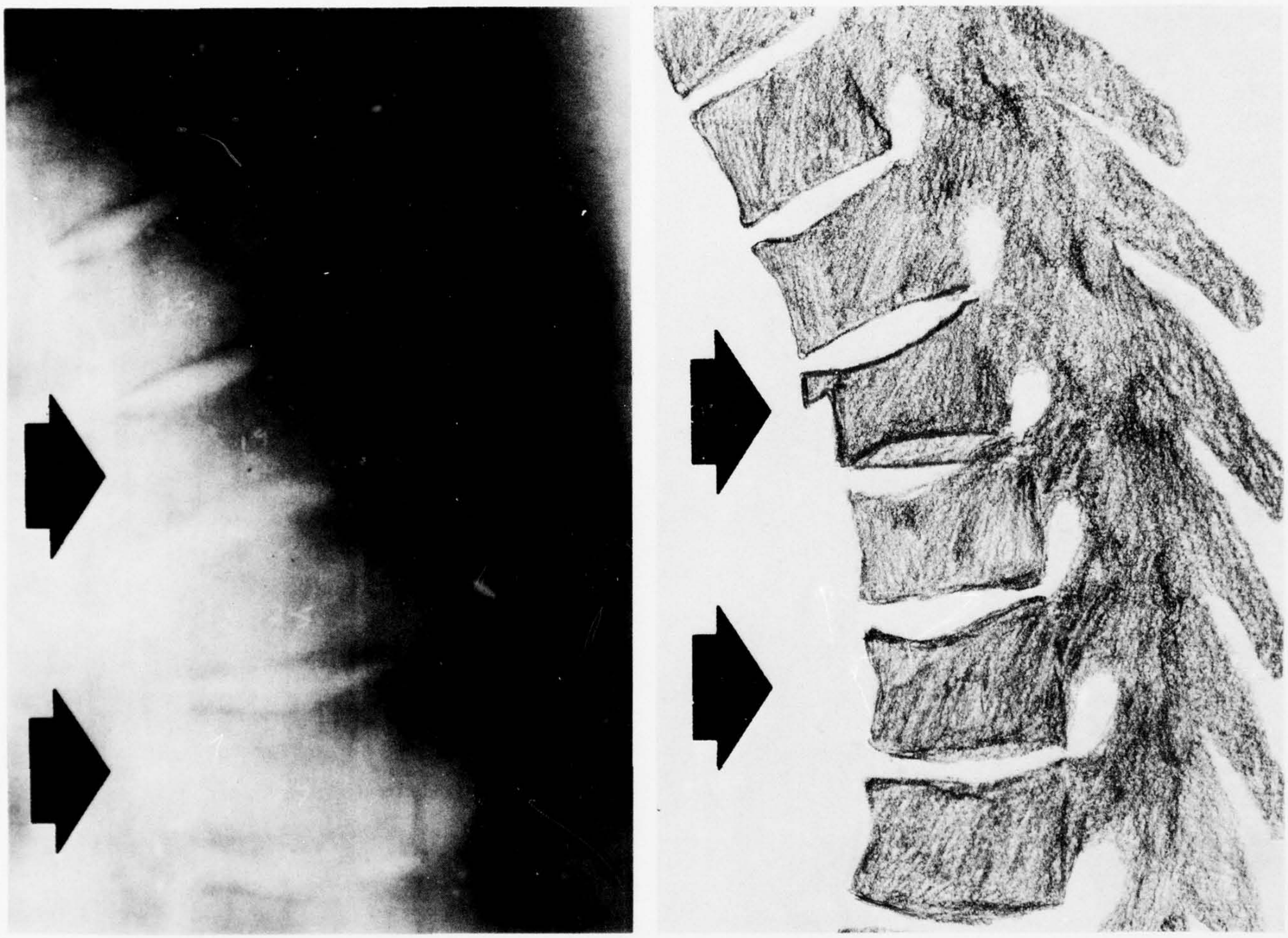


Figure 17. Lateral View of Upper Thoracic Spine. Avulsion Fracture of the Anterosuperior Segment of T_6 and T_8

ANTERIOR WEDGE COMPRESSION FRACTURES (HYPERFLEXION FRACTURES)

Anterior wedge compression fractures are the result of acute flexion of the upper thoracic spine that collapses the vertebral centrum at the point of maximum spinal compression, corresponding to the region of maximum stress in hyperflexion within an unrestrained torso. Hyperflexion injuries with compression of the vertebral centrum roentgenographically appear to be of varying degrees of severity involving the superior half of the vertebral body. Such hyperflexion injuries may be pictured in one of three ways in order of increasing severity. The first is a partial uniform collapse of a vertebral body at its anterior and posterior heights in the T_5-T_6 region, as illustrated in Figure 18. The second usually involves multiple vertebral bodies with collapse of two or three vertebral bodies, as illustrated in Figure 19. The third involves compression of the anterior vertebral centrum height at several vertebral levels, but, in addition, there may occur fractures of the vertebral pedicles and/or articular facets, as radiographically shown in Figure 20, with relatively large vertebral body displacement and kyphotic angulation. The spinous process of the affected vertebra is separated from that of the superior vertebra toward its tip. Rupture of the interspinous ligament is common. The ligament may be overstretched, partially torn or completely ruptured, with or without avulsion fracture of the spinous process. Fourteen aircrewmen have sustained anterior wedge compression fractures.

COMBINED ANTERIOR WEDGE/POSTERIOR HEIGHT COMPRESSION FRACTURES

Combined injuries, those resulting from extension and flexion, are of the upper dorsal spinal column and are relatively common. Frequently the dorsal spine will be fractured at multiple locations. Whether fractures occur in the same, adjacent or distant vertebrae is dependent upon the relative geometries of the support and restraint system, the driving forces, and the kinesiology of the upper torso with respect to the support and restraint system. The radiograph illustrated in Figure 21 demonstrates a combined injury mode that occurred due to two separate forces acting in sequence.

BURST INJURIES

Vertebral centrum fracture fragments may be derived in several ways. Vertical split compression injuries occur only in those regions of the spinal column where the vertebral bodies are sufficiently immobile so that the impact loads are directly transmitted from one vertebra to the next with minimum angulations. The primary fracture line is a vertical cleavage of the body, forming large fragments with no trabecular bone impaction. Often, there is a dispersion of bony fragment anteriorly. The longitudinal ligaments remain intact. An example of a combined injury mode in addition to a burst injury is shown also in Figure 21 (circled area). Two aircrewmen sustained burst injuries.

LATERAL WEDGE COMPRESSION FRACTURES.

The lateral wedge compression fracture is a flexion rotation injury. This injury is usually followed by a varying degree of scoliosis. It is complicated by injury to the articular facet joints on the concave side of the vertebral body, as roentgenographically shown earlier in Figure 5. Two aircrewmen sustained this injury mode, in addition to those described earlier. Two other crewmen sustained lateral wedge compression fractures. Lateral wedge compression fractures with a rotational deformity are usually the result of an aircrewman with a tall sitting height, sitting with his seat near the "FULL UP" position. (The void between the head rest and seat back is minimal.) A scoliosis results over two or three vertebrae. The burst and lateral wedge compression fractures are considered to be variations of anterior wedge compression fractures.

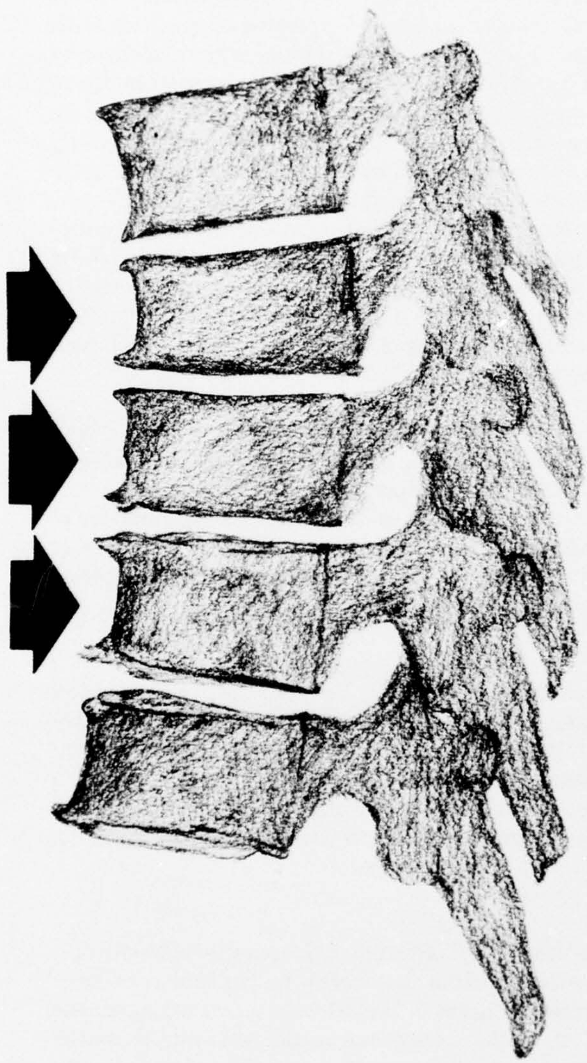


Figure 18. Lateral View of Upper Thoracic Spine Illustrates Uniform-like Collapse of Vertebral Centrum Height

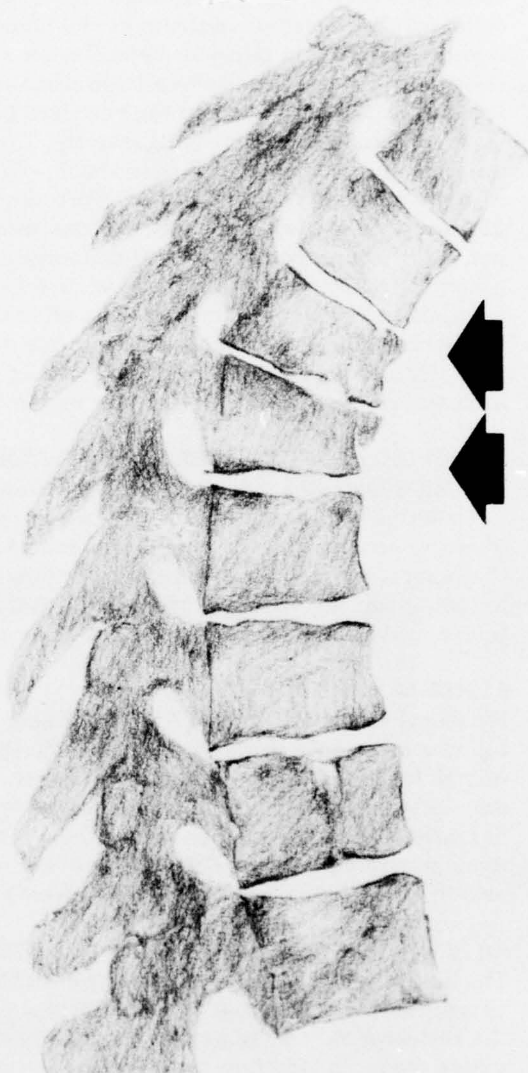


Figure 19. Lateral View of Upper Thoracic Spine Illustrates Anterior Vertebral Centrum Collapse at Two Levels

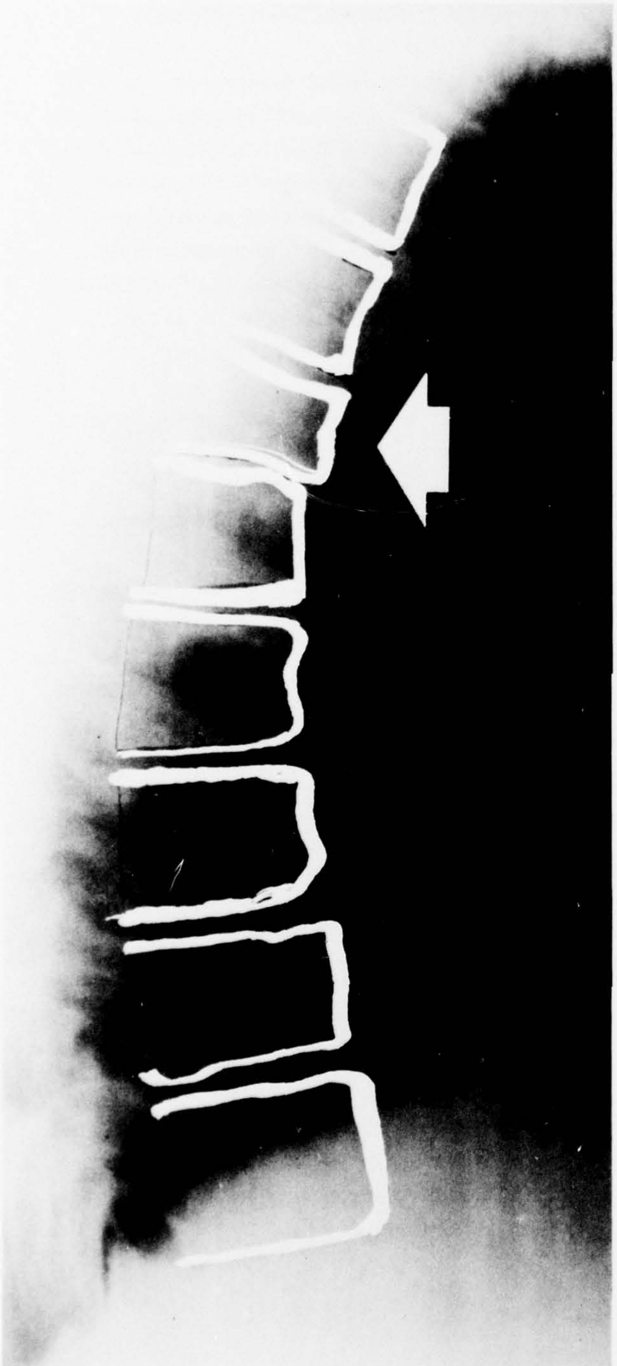


Figure 20. Lateral Radiograph Shows Combined Anterior Wedge Compression Fracture and Disruption of Posterior Vertebral Column

Figure 21. Combined Injury Mode in Addition to a Burst Injury Due to Vertical Impact Loading (Circled Vertebra)

COMPARISONS OF SPINAL INJURY FREQUENCY AND DISTRIBUTIONS OF F/FB-111 VERSUS THOSE OF OTHER AIRCRAFT

(The Latter Are Comprised of Data From Open Seat Ejections, Light Aircraft Crashes, and Non-Aircraft Related Clinical Experiences)

Figure 22 compares the level and frequency of other operational injury statistics to those observed in the escape module. In the open ejection seat experience, fractures occur most frequently in the spinal region $T_{10}-T_{12}$, excepting in a single reported series by Hirsch and Nachemson (1963), who conducted orthopedic evaluations of Royal Swedish Air Force ejectees and showed a predominance of anterior wedge compression fractures in the thoracic spine. The incidence, distribution, and level of spinal fractures reported by Hirsch and Nachemson are given. The data presented by Hirsch and Nachemson indicate multiple injury modes predominate over the length of the spinal column, whereas the F-111 data (Kazarian 1976) reflect a localization of spinal injuries in the upper thoracic column. Hirsch and Nachemson made no reference to aircraft type, restraint system, powered inertia reels, etc.

Ewing's data (1975)*, based upon U.S. Navy ejection statistics, reflect the peak in the spinal injury level to occur in the region T_8-L_1.

Kaplan's data (1972), based upon U.S. Army statistics, show two peaks, one at T_8 and the other at L_1.

Nicoll's data (1949), based upon non-aircraft related injuries, indicate that 66% of spinal injuries are confined to three vertebral levels, T_{12}, L_1, and L_2.

Jefferson's statistics (1927) illustrate the distribution of clinical spinal injury. The predominance of injuries occur in the C_6, C_7, T_1 region and at the T_{12}, L_1 level.

The spinal injuries sustained in the cases of Jefferson and Nicoll seem to correspond nicely to the structural changeover in articular facet plane orientation between the cervical/thoracic and thoracic/lumbar spinal column.

The spinal injury data of Ewing and Kaplan show a bimodal injury distribution. That is to say, that in addition to injuries sustained in the region of the critical changeover in the articular facet joint planes of the thoracolumbar column, spinal injury occurs at a relatively immobile region of the spine ($T_8-T_9-T_{10}$).

The occurrence of upper thoracic anterior wedge compression fractures in the operational flying and related accident/emergency escape environment were documented previously only by Hirsch and Nachemson. Anterior wedge compression fractures of the upper thoracic spine are a common occurrence in the F/FB-111 crew escape module. Hyperextension posterior wedge compression fractures (hyperextension injuries) of the thoracic spine have not been previously documented.

Ewing, C.: Personal Communication, April 1975

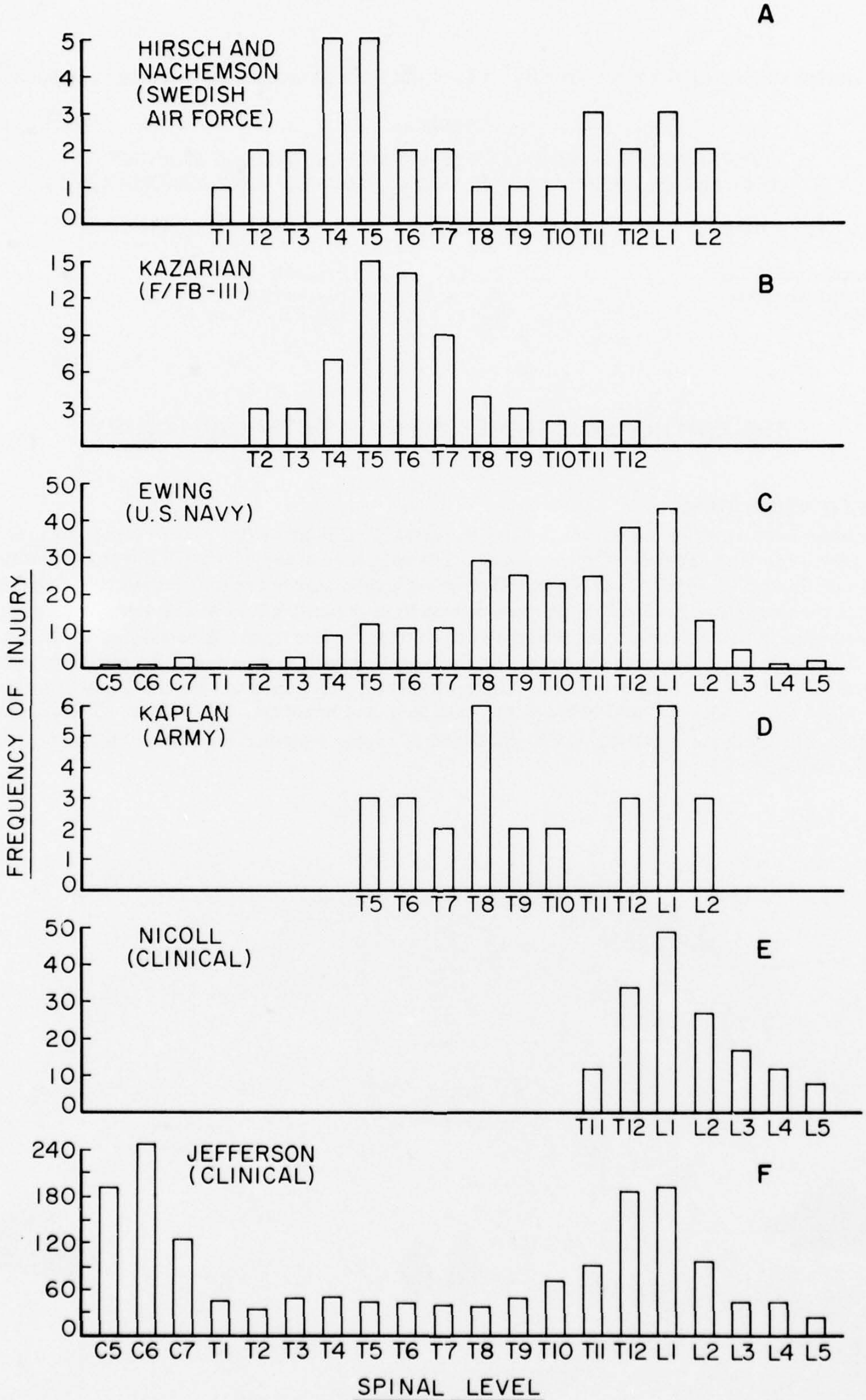


Figure 22. A Comparison Between the Level and Frequency of Operational/Clinical Injury Statistics to Those Observed in the Escape Module

Table 1 lists the spinal regions most often injured in light aircraft or helicopter crashes and open ejection seats.

Table 1

SPINAL REGIONS MOST AND LEAST OFTEN INJURED IN LIGHT AIRCRAFT OR HELICOPTER CRASHES AND OPEN EJECTION SEATS

CAUSE OF INJURY	*MOST COMMON SITE*	*LEAST COMMON SITE*
Light Aircraft Crash	$T_{10}-L_2$	Upper/Mid Thoracic
Helicopter Crash	$T_{10}-L_2$	Low Lumbar
Ejection	$T_{12}-L_1$	Upper/Mid Thoracic

THE ORTHOPEDIC BIOMECHANICS OF SPINAL INJURY

HYPEREXTENSION TYPE

All hyperextension injuries were categorized in terms of seat geometry with respect to aircrew anthropometry, type, and severity of spinal injury. The sequence of injury was found to be as follows: on powered inertia reel retraction, the horse collar was dragged across the upper surfaces of the clavicles applying a rearward, arcing force on the acromioclavicular joints while at the same time placing the sternoclavicular joints in tension, as illustrated in Figure 23. The upper torso reacted to the retraction force by forcing the scapulae into the posterior chest wall, which restrained and locked the ends of the upper ribs into the T_1-T_7 vertebrae. Thus, the backrest formed a fulcrum for the upper position of the thoracic spine to arc into the void between the seat back and headrest. This injury is due primarily to normal thoracic kyphosis dearcing. The sequence of events required to produce this injury mode are illustrated in Figure 24.

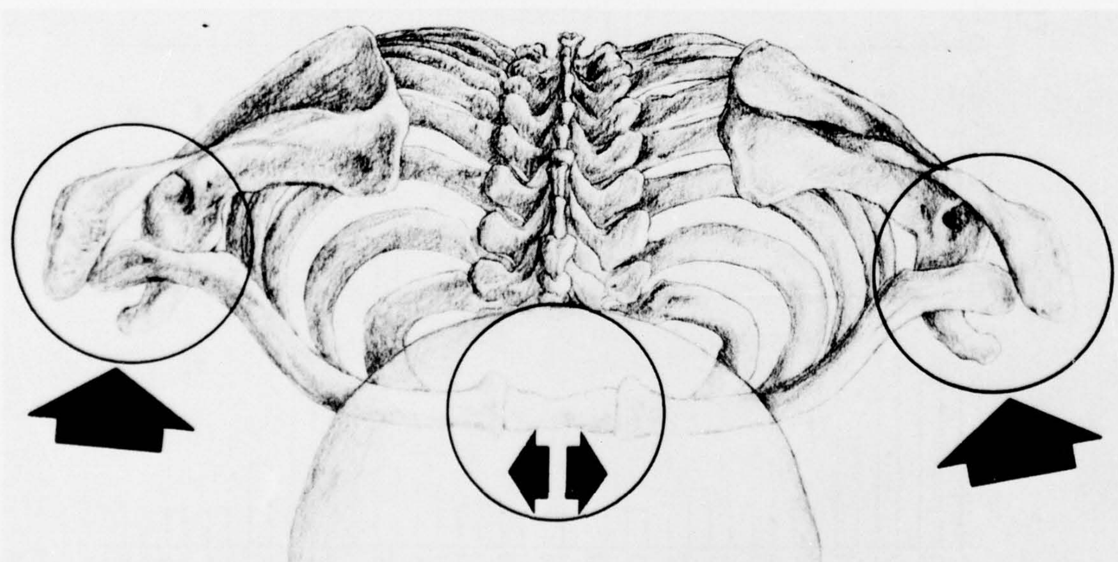


Figure 23. Top View of Head and Torso Exhibits the Action of the Powered Inertia Reel on the Shoulders. As a Result of Powered Inertia Reel Retraction, the Sternoclavicular Joints are Placed in Tension.

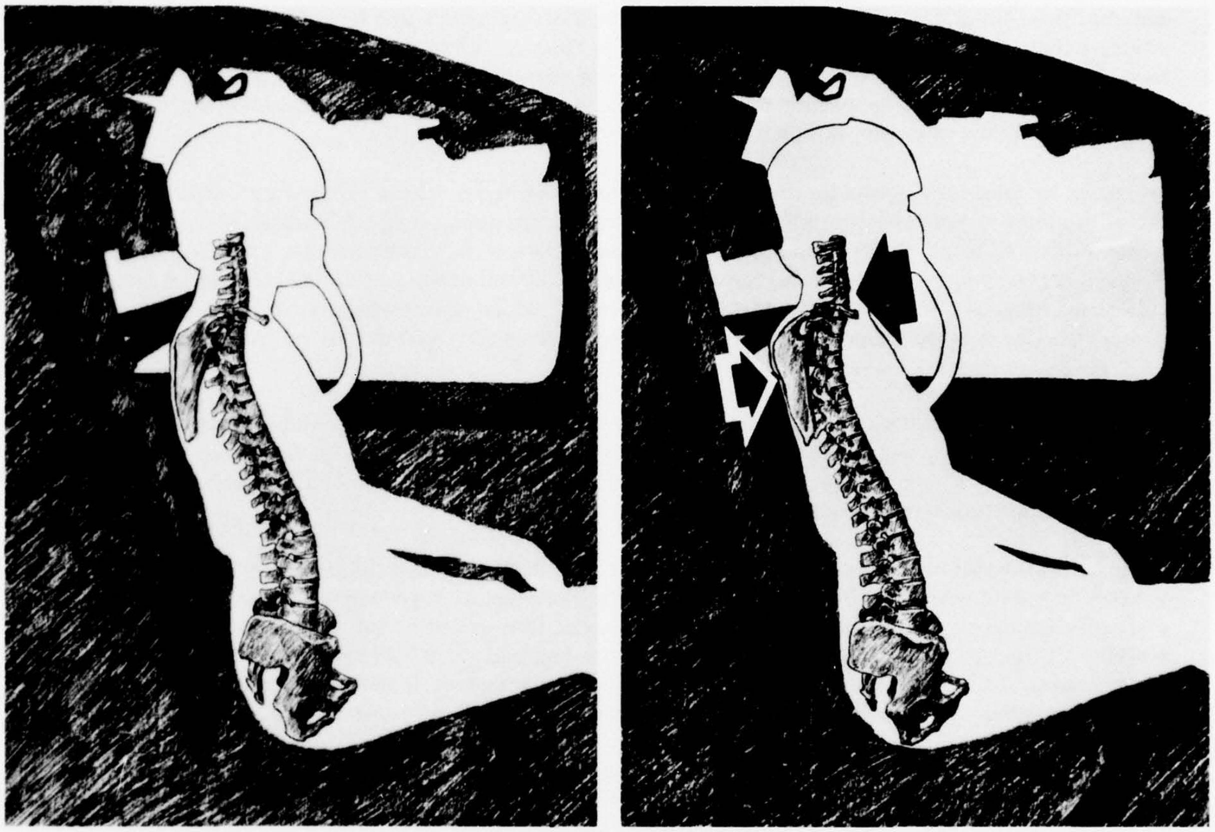


Figure 24. Arcing Hyperextension Injury of Upper Thoracic Spine, a Fulcrum is Formed by the Seat Back as the Powered Inertia Reel Decreases and Reverses Thoracic Kyphosis. Left: Normal Torso Position. Right: Inertial Reel Retracted.

A second hyperextension injury mode was also identified. As in the injury mode just described, the normal curvature of the thoracic spine is reversed placing the anterior longitudinal ligament in tension; however, in this second hyperextension injury mode, there occurs simultaneously a downward, rearward, medially-directed load inward that causes posterior vertebral centrum compression in the mid-thoracic column. In addition, the spinous processes and articular processes are forced together and act as a fulcrum, causing the anterior longitudinal ligament to rupture. It has been strongly suspected that separation has occurred between the cancellous bone of the vertebral body and the adjacent cartilaginous end plate. Fractures of the accessory processes have occurred without fractures to the vertebral body. This second hyperextension injury mode is illustrated in Figure 25.

In either hyperextension mode, the spinal injuries sustained by these aircrewmen are clearly due to forceful, upper vertebral column reversal, or attempted reversal, along with a downward and medially inward-directed force, which then indirectly produces disruption of the anterior longitudinal ligament. The above injury pattern and its degree of severity are related to the position of the inertia reel and the reflecting shoulder strap anchor points with respect to an aircrewman's sitting height and seat geometry. The void between the headrest and seat back is also a contributing factor to the injury.

HYPERFLEXION TYPE

Anterior wedge compression fractures are the result of acute flexion by indirect violence through forcible exaggeration of normal upper spinal curvature. (All anterior wedge fractures in aircrewmen who have utilized the crew escape system are due to forcible spinal flexion, which secondarily results in forcible exaggeration of normal spinal curvature.)

Based upon the pendulum action of the crew escape module during descent, it was hypothesized the crew module does not make an uniform landing on its impact attenuation system. Accident investigation data distinctly indicate that the point of crew module impact is its right or left rear corner on the downward pendulum action brought about by impact attentuation bag and parachute dynamics. As a result, the effectiveness of the impact attentuation system of the crew module is compromised, and the aircrewmen undergo a combination of G_zG_x ground landing impact forces rather than a pure G_z impact force.

The hyperflexion spinal injury patterns experienced by all aircrewmen were identical. I decided to scrutinize the effectiveness of the F/FB-111 harness system with respect to torso hyperflexion, resulting in the following information. The lap belt provided excellent pelvic stability; however, because the reflecting shoulder straps are anchored below shoulder level, they allow the upper torso to rotate within the fully retracted and locked harness, as shown in Figure 26. The sequential biomechanics of hyperflexion spinal injury are illustrated in Figures 27 and 28. Bursting injuries of the vertebral centrum are the result of the primary ground landing impact force applied in a vertical direction with a much smaller component in flexion.

The current F/FB-111 restraint geometry does not provide optimum overall protection in the crew module environment. The position and action of the inertia reel and the shoulder straps anchor position have compromised, to the worst possible degree, the support and restraint offered by this system.

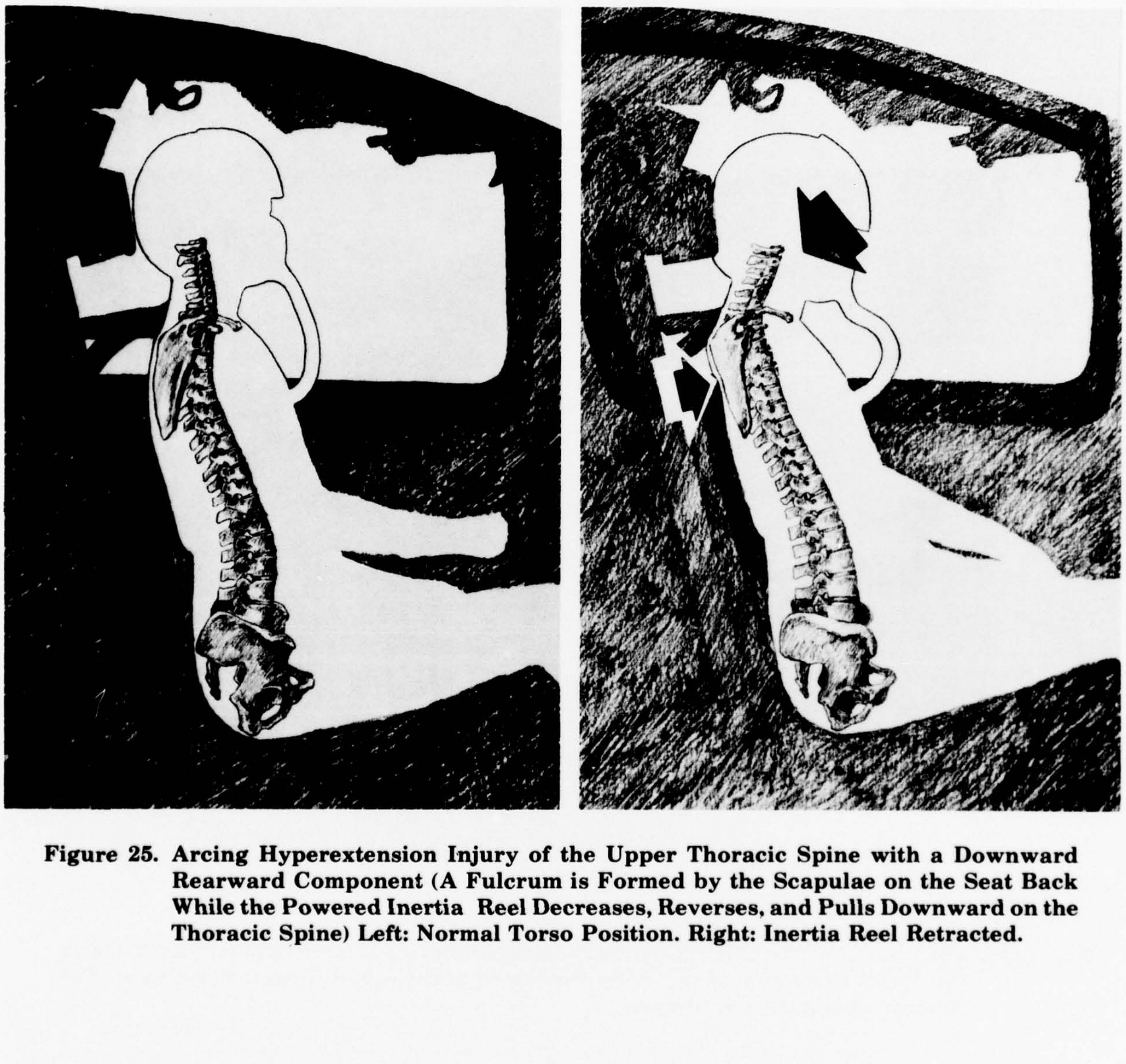


Figure 25. Arcing Hyperextension Injury of the Upper Thoracic Spine with a Downward Rearward Component (A Fulcrum is Formed by the Scapulae on the Seat Back While the Powered Inertia Reel Decreases, Reverses, and Pulls Downward on the Thoracic Spine) Left: Normal Torso Position. Right: Inertia Reel Retracted.

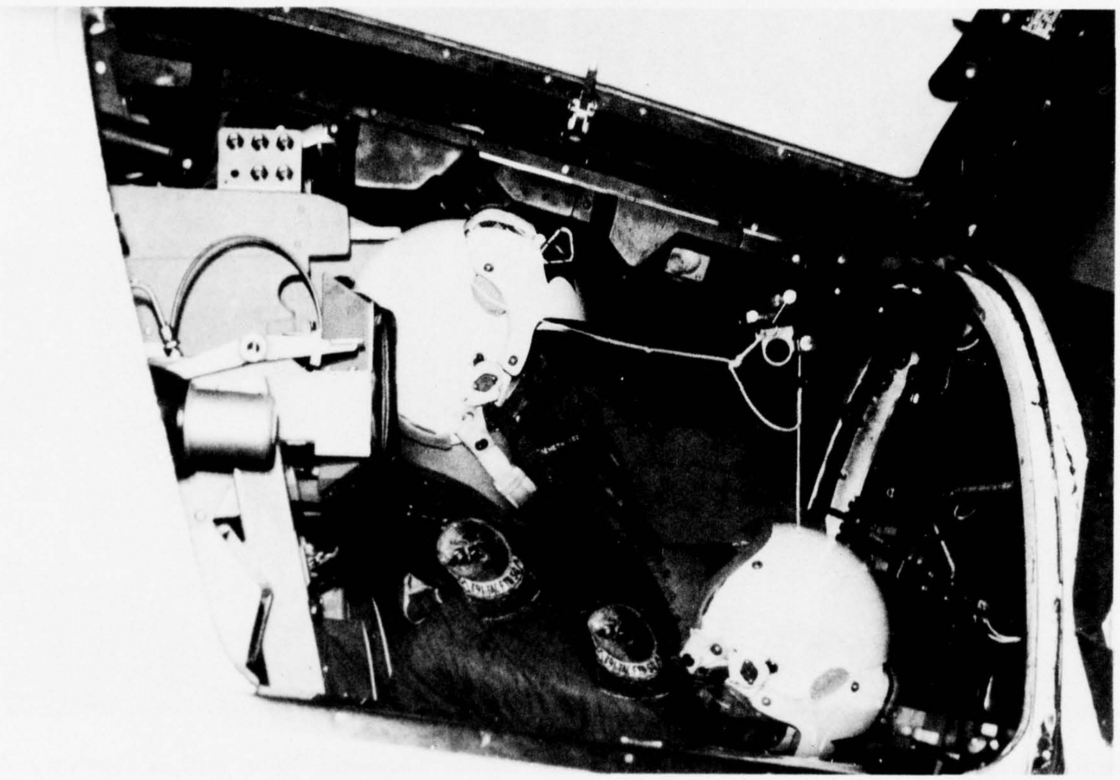


Figure 26. The Configuration of the Restraint System Allows an Aircrewman to Rotate Within the Fixed Geometry of the Fully Retracted and Locked Restraint Harness. The Amount of Rotation is Shown.

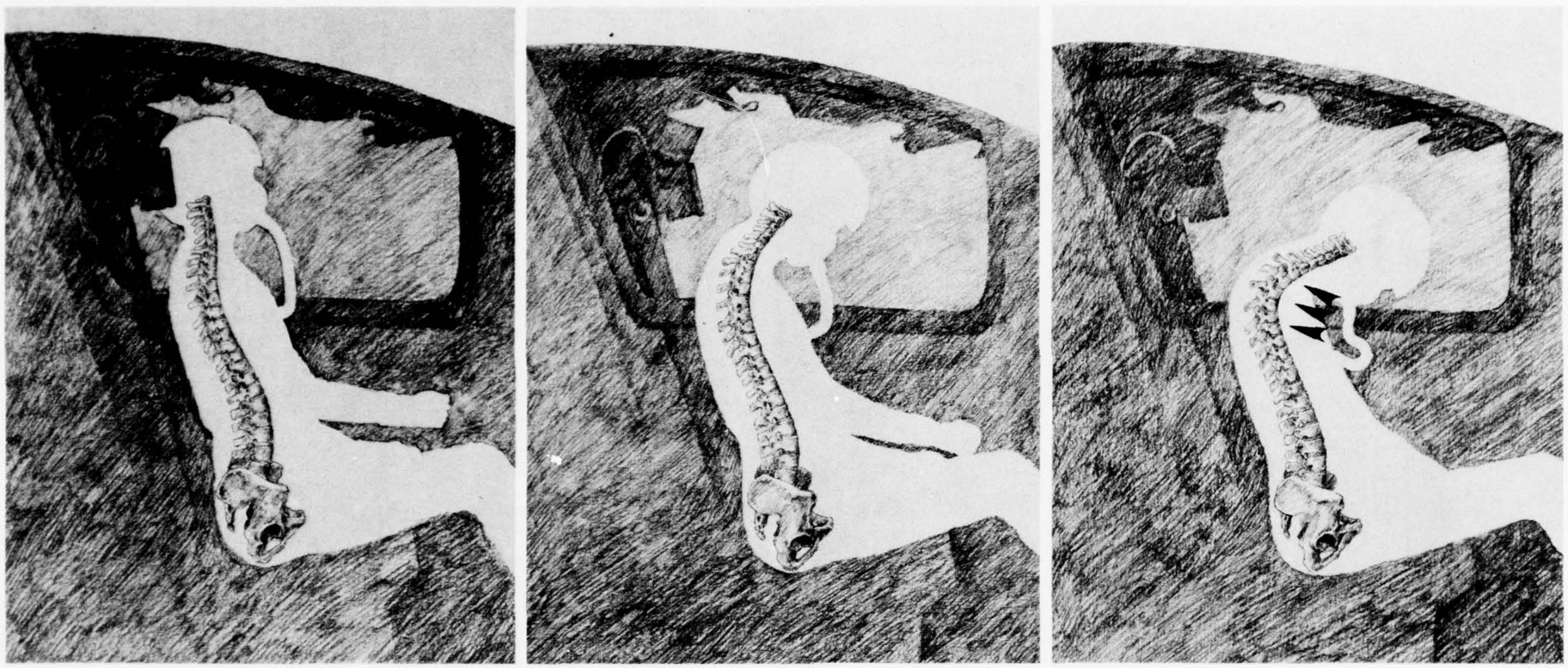


Figure 27. Sequence of Spinal Kinesiology as a Result of Crew Module on Ground Landing Impact

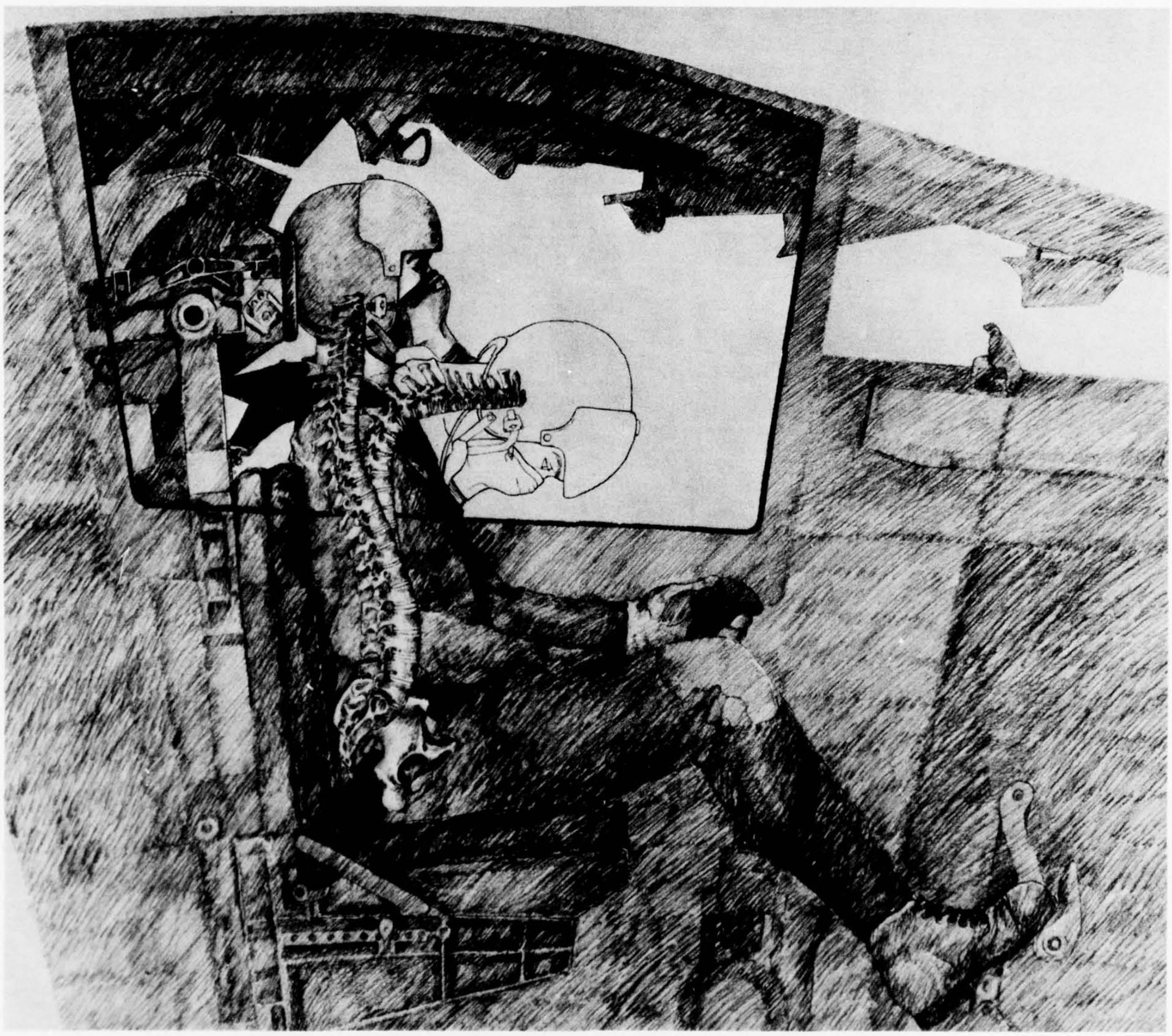


Figure 28. Sequence of Spinal Kinesiology as a Result of Crew Module on Ground Landing Impact

SCHEME FOR INTERPRETATION AND CLASSIFICATION OF F/FB-111 SPINAL INJURY

The scheme for the classification of F/FB-111 spinal injuries, shown in Figure 29, is based upon all available spinal injury roentgenograms reviewed as of 30 June 1977. The severity of spinal injury increases from Type 1 to type 3, as it does from Type A to Type C. An aircrewman may experience either one or a combination of hyperextension or hyperflexion injuries. Hyperextensions are due to the action of the powered inertia reel and shoulder strap anchors. Hyperflexion injuries are the result of ground landing impact forces and the inability of the harness to restrain the crewmember. A single injury mode is identified as a Type 1, etc., or Type A, whereas, a combination injury mode is identified as Type 1A or Type 1C, etc.

AN INTERIM SOLUTION TO HYPERFLEXION INJURIES; T.O. 1F-111F-1SS-39

Following a major aircraft accident on 20 June 1975, I recommended that a new body position be incorporated into the emergency procedures to minimize hyperflexion injuries due to the $+G_x$ response of the upper torso following ground landing impact. The body position selected is shown in Figure 30. It varies in appearance depending upon crewmember anthropometry. Each crewmember is trained to be familiar with this positioning procedure as it applies to himself and to be capable of assuming it in minimal time.

The sequence is as follows:

(1) Shoulder harness — locked

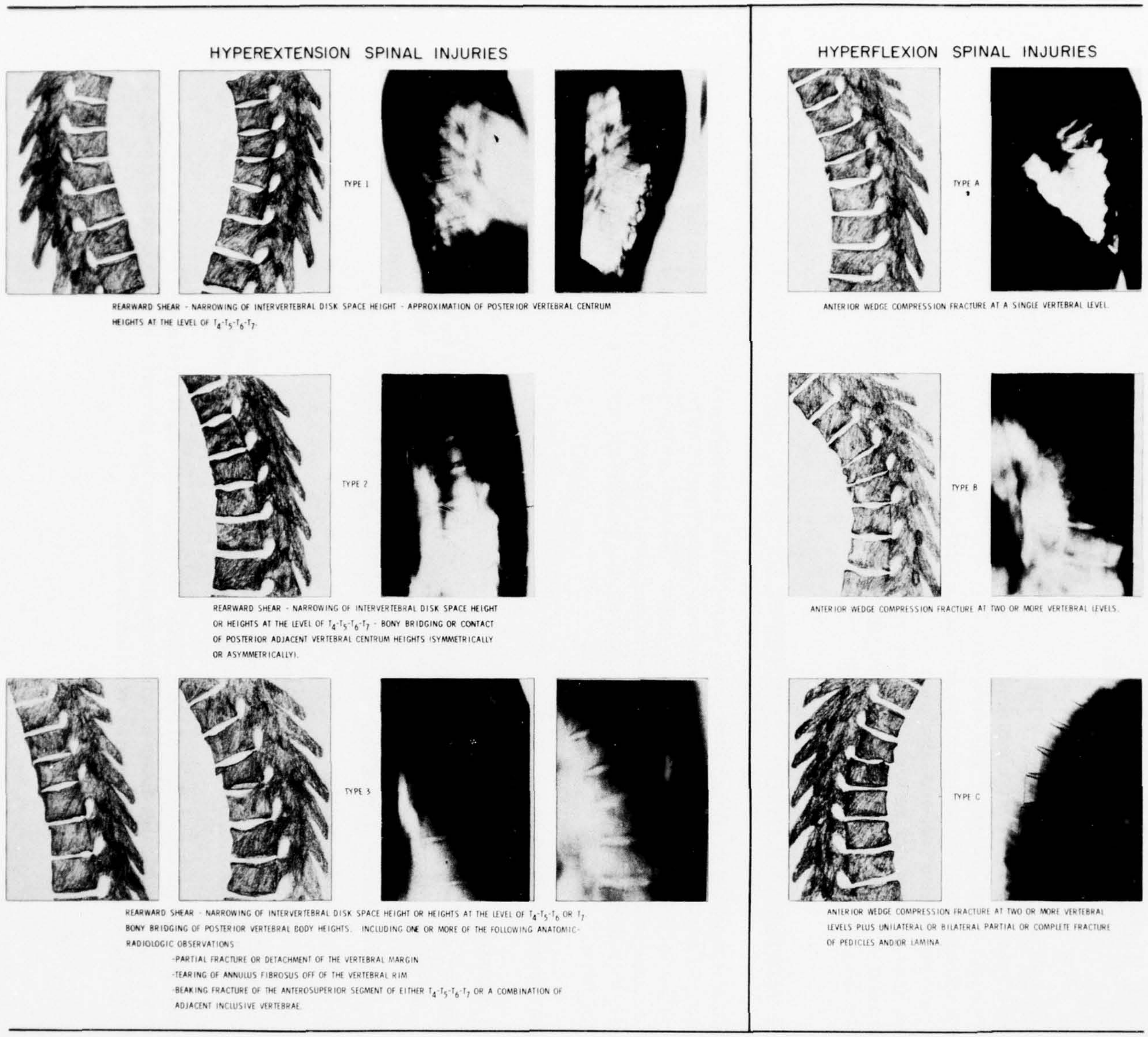
(2) Seat pan — forward to optimum position. The seat pan should be moved as far forward as possible without causing leg contact with the instrument panel. With the shoulder harness locked, this motion causes a tightening of the upper torso harness and minimizes the possibility of a forward rotation of the upper body during ground landing impact.

(3) Feet on rudder pedals.

(4) Back and head held firmly against seat and headrest.

(5) Arms crossed in front of head, firmly grasping the shoulder harness straps as far aft as possible. Raise elbows until pocket formed by the arms is firmly in contact with the face mask assembly.

Since the initiation of this technical order (T.O.), 20 aircrewmen have ejected. No hyperflexion injuries have been radiographically detected where an aircrewman has partially or fully complied with this procedure. Hyperextension fractures continue to occur.

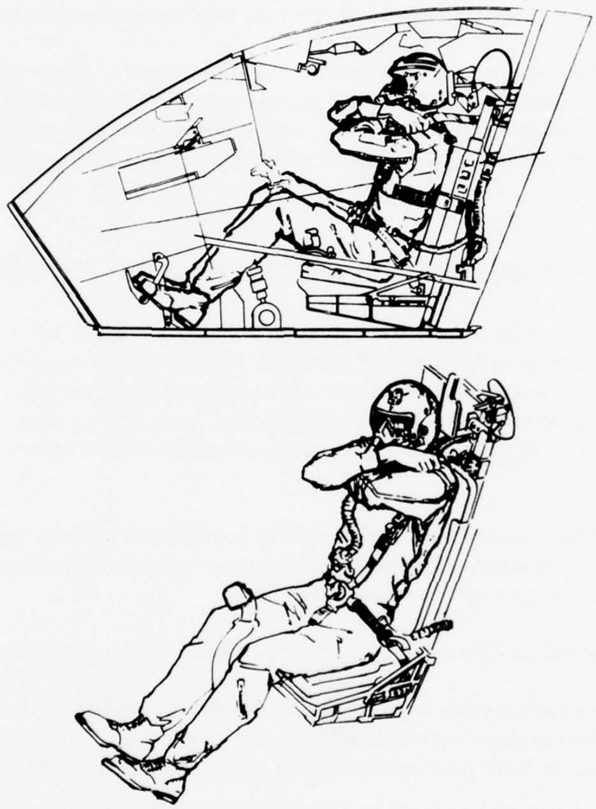


THE SEVERITY OF INJURY INCREASES FROM TYPE 1 TO TYPE 3 AS IT DOES IN THE CASE OF TYPE A TO TYPE C. **AN AIRCREWMAN MAY EXPERIENCE EITHER / OR A COMBINATION OF INJURIES.** A SINGLE INJURY MODE IS IDENTIFIED AS TYPE 1, ETC. OR TYPE A, ETC., **WHEREAS A COMBINATION INJURY MODE** IS IDENTIFIED AS TYPE 1A, OR TYPE 1C, ETC.

Figure 29. Classification and Interpretation of Spinal Injuries Due to Ejection Forces

T.O. 1F-111(B)A-1 Section III Emergency Procedures

Recommended Body Position For Ground Impact



Change 4 3-22A

Figure 30. Technical Order 1F-111F-1SS-39

SOLUTIONS TO THE PROBLEM OF F/FB-111 SPINAL INJURIES

The spinal injuries reported herein are due to:

- Adverse geometric reactions of the inertia reel and shoulder straps with the upper torso following ejection initiation.
- The $+G_x$ reaction of the torso following G_z ground landing impact forces.

If the position and/or the geometry of the inertia reel and the shoulder strap anchor points are raised upwards above a crewman's shoulders, both injury modes will be significantly reduced. At the time of this writing, a statement of work has been written, and a program will be started in August 1977 to correct the design deficiencies in the support and restraint system that will significantly reduce the back injury problem.

FOLLOW-UP STUDY OF INJURED F/FB-111 CREWMEN

To date, follow-up radiographic studies have been conducted on all available F/FB-111 ejectees, usually supplemented by a linear tomographic survey, which is extemporized according to injury level and mode. Tomographic investigations have made it possible to clearly localize the site of spinal fracture, to obtain information on the condition of the posterior vertebral arch, and to elicit a profile of intradiskal injuries showing whether the longitudinal or interspinous ligaments and intersomatic disks have been ruptured or not.

The most frequent radiographic injury profile observed in hard tissue trauma was found to occur in the upper and mid-thoracic spinal column. All hard tissue injuries were classified according to region, type, and severity. The mechanics of injury have been identified.

Based upon the data presented in this report, some very interesting points were brought to light:

- A roentgenographic examination carried out only once immediately following ejection yields little conclusive evidence about soft or hard tissue changes resulting from ejection trauma. This is true even if the immediate postejection spine films are initially interpreted as normal.
- End plate fractures, symmetric or asymmetric articular facets, or pedicular fractures are difficult to detect immediately following acute trauma.
- Ejectees have a high rate of symptomatic spinal disorder many months and even years following the ejection.

From a scientific point of view, there is a lack of systematic pathologicoanatomic investigation dealing with spinal trauma, yet there exists a definite biomechanical, operational, and clinical need to recognize and diagnose acute and pathologic changes in hard and soft tissue and in the kinesiologic interrelationships between the disks, vertebral bodies, and torso.

Information characterizing occult spinal injury would improve the definition of failure criteria and failure limits. The exact recognition and early diagnosis of spinal injury would assist in defining its proper management path and shed light on its long-term physiopathologic changes.

The justification for serial examination is illustrated in the following representative case histories.

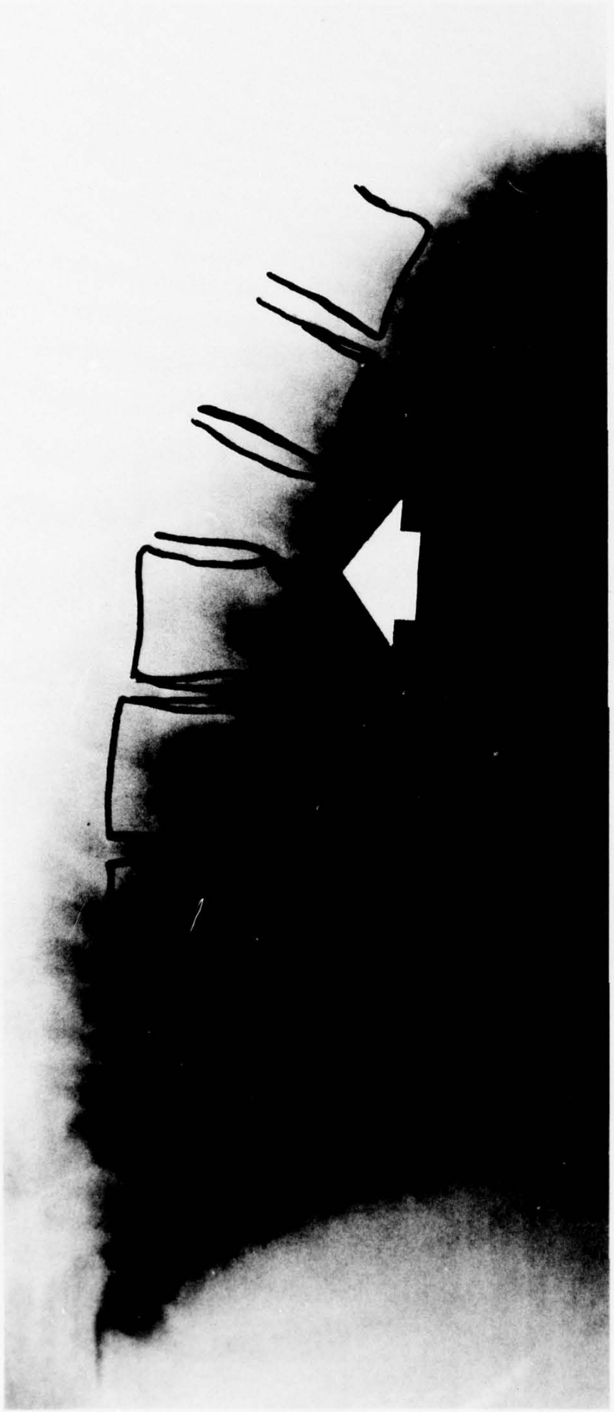


Figure 31. Lateral View of Thoracic Spine Shows Ground Landing Impact Injury (Subject PA)

Figure 32. Lateral View of Thoracic Spine of Subject PA 6 Weeks After Ejection Trauma

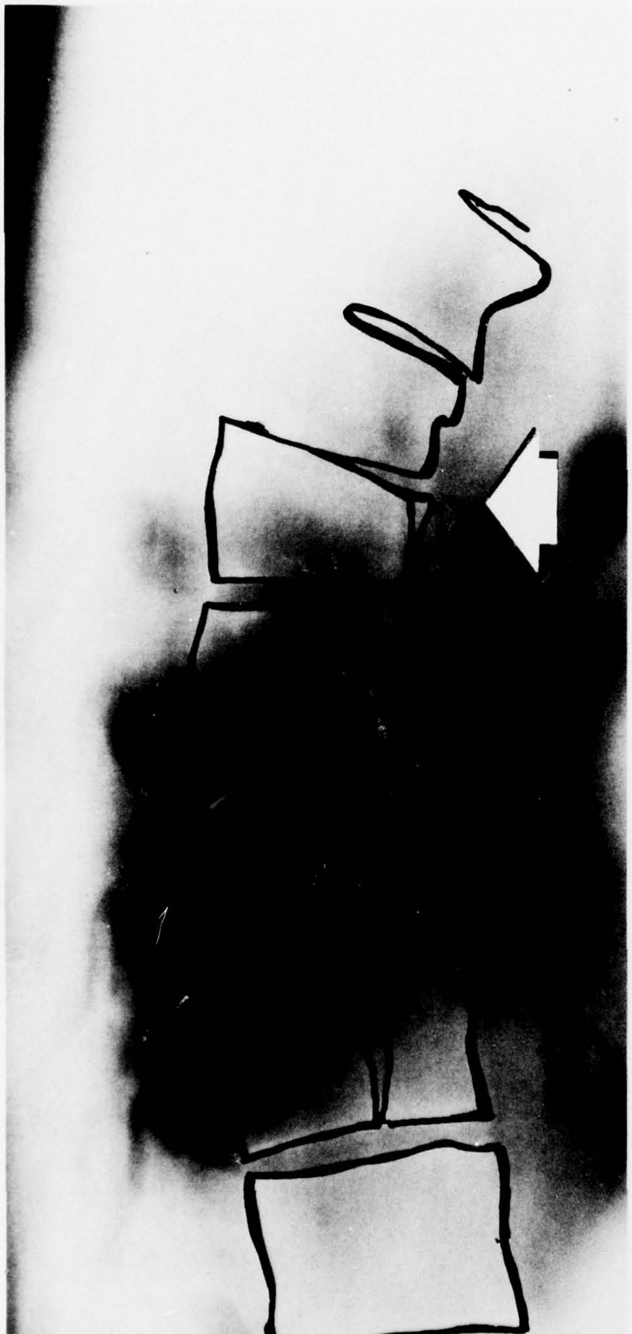


Figure 33. Lateral View of Thoracic Spine of Subject PA 4 Months After Ejection Trauma [Note Loss in Intervertebral Disk Space Height (Arrow)]

Figure 34. Lateral View of Thoracic Spine of Subject PA 18 Months After Ejection [Arrows Identify Spinal Region Undergoing Spontaneous Anterior Fusion]

Case I — Subject PA sustained a Type 3C injury after ejection. The injury is shown in Figure 31. He was placed in a body cast for 6 weeks. Following this period, the cast was removed. Roentgenograms showed good vertebral column alignment. Intervertebral disk space was maintained as shown in Figure 32. Four months after ejection injury, additional radiographs were taken. A kyphotic angulation along with a decrease in intervertebral space height and further vertebral body compression were found (Figure 33). Eighteen months following ejection, radiographs were repeated; Figure 34 shows that the spinal level of involvement at this period of time was in the process of undergoing a spontaneous anterior fusion with a permanent gibbus deformity.

Case II — Figure 35 is a lateral roentgenogram of a sagittal section of the mid-thoracic spine of Subject TI. It shows a compression fracture of the superior aspect of the centrum of the 6th dorsal vertebra, with separation and displacement of a large fragment of the centrum. Roentgenograms were repeated 4 days later (Figure 36). The injury pattern was further defined. Sixteen weeks after trauma, secondary and recognizable sequelae included dimunition of intervertebral disk space along with a bony fragment between the T_6-T_7 intervertebral disk space level. Thirty-two weeks after injury, further dimunition of intervertebral disk space was noted at the T_5-T_6, T_6-T_7 levels. A previously unsuspected bony fragment was clearly evident; see Figure 37. Sixty-four weeks following trauma, a bony fusion was noted to be developing at the T_5-T_6 vertebral level, as observed in Figure 38.

The clinical evaluation of roentgenograms made immediately after spinal injury frequently leaves doubt as to the extent of spinal injury. The true extent of spinal injury can only be identified subsequently by the occurrence of late, secondary roentgenologic changes. Experience has clearly demonstrated that these facts have not been sufficiently considered in treatment. Lesions of the intervertebral disks, long ligaments and posterior articular facet joints initially undetected are usually also brought out by comparative roentgenographic analysis. Injuries such as cortical wall buckling and avulsion of the long ligaments are usually associated with the formation of a hematoma. Some evidence collected to date suggests that if the periosteum is injured due to extravasated blood, ossification with subsequent calcification may occur. In the early stages of calcium deposition, roentgenograms will show a cloudy shadow that may somewhat blur the outline of the vertebrae involved. Subsequent radiographs may indicate, at the site of trauma, localized thickening and/or sclerosis of the vertebral cortex.

When these morphologic changes have been radiographically indicated in the vertebral joint, the following were noted to occur: diminution of intervertebral disk space height, lipping of the adjacent margins of the vertebral centra, localized calcification of the anterior longitudinal ligament, and eburnation and erosion of the articular facet joints due to overstressing. These localized anatomicopathological changes bring about a limitation in the range of motion of the thoracic spine, along with a loss in interverbral joint viscoelasticity and impact/shock absorbing capacity.

Figure 35. Lateral Roentgenogram of Subject TI After Crew Module Ejection and Ground Landing Impact [Arrow Points to Injured Spinal Region]

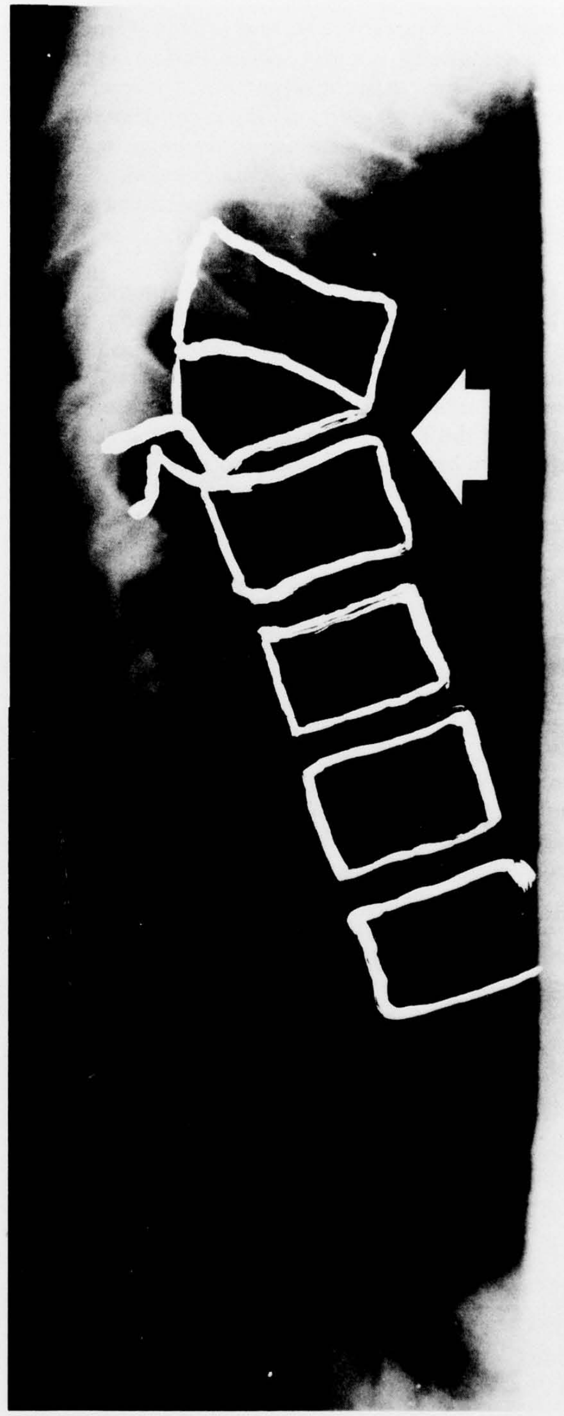


Figure 36. Lateral Roentgenogram of Subject TI 4 Days After Ejection [Arrow Identifies Site of Anterior Wedge Compression Fracture]

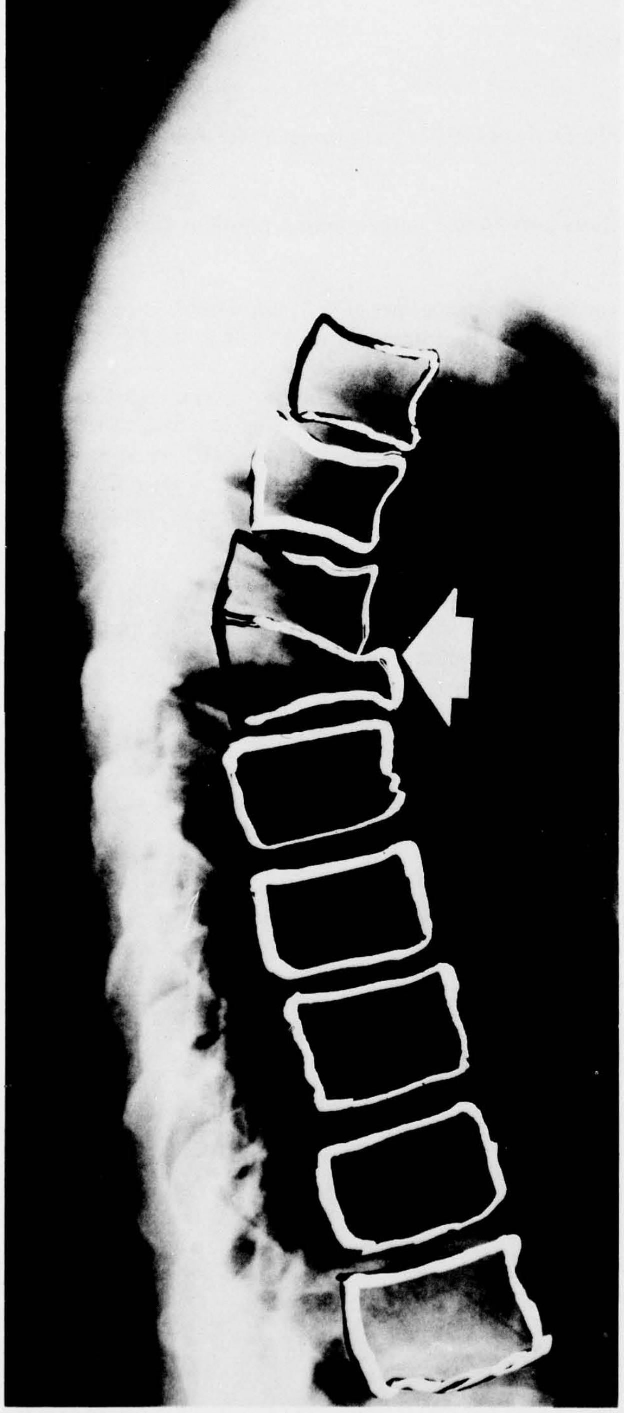


Figure 37. Lateral Roentgenogram of Subject TI 32 Weeks After Spinal Injury [Bony Fragment is Clearly Visible]

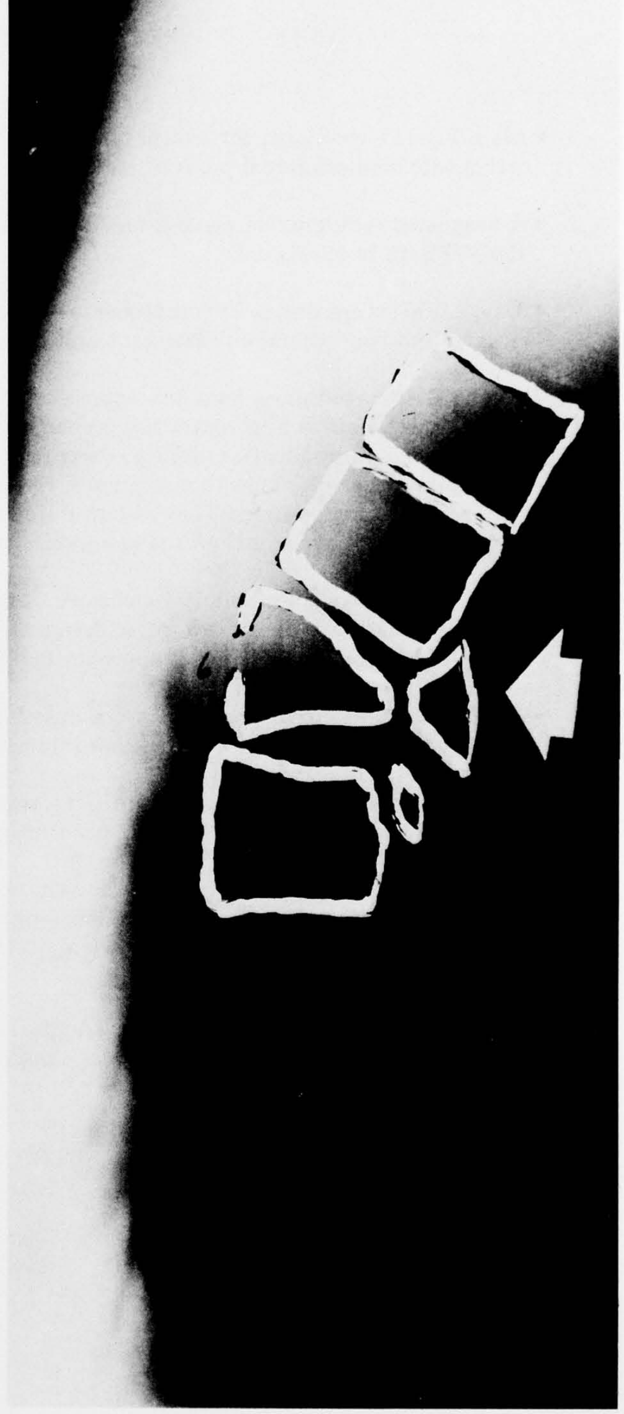


Figure 38. Lateral Roentgenogram of Subject TI 64 Weeks After Ejection [Bony Fusion is Noted to be Occurring]

SUMMARY

- All F/FB-111 ejections, for the period October 1967 to June 1977, have been reviewed from an orthopedic biomechanical point of view.

- A suggested radiographic method for identifying and classifying the unique spinal injury patterns in the F/FB-111 is presented.

- A type of fracture due to hyperextension of the upper thoracic spine, previously unidentified in the clinical and operational environment and having clinically unfamiliar features, is described.

- F/FB-111 spinal injuries have been classed as (a) hyperextension injuries, (b) hyperflexion injuries, and (c) combination hyperextension/hyperflexion injuries. Hyperextension injuries are due to the direction of force application of the powered inertia reel, and they occur during the powered inertia reel retraction phase of the ejection sequence. Hyperflexion injuries are due to the ineffectiveness of the upper torso harness, and they occur following ground landing impact. Combination injuries (hyperextension/hyperflexion) are common.

- The mechanism of spinal injury in most aircrewmen is best understood and most often diagnosed by a combination of careful aircrew questioning, clinical history, and thorough roentgenographic assessment. The operational, clinical, and roentgenographic features should be complementary.

- A new technical order has been incorporated into the F/FB-111 emergency escape procedures. The severity and frequency of hyperflexion injuries have been reduced.

- The design deficiency in the configuration of the support and restraint system has been identified, with the result that corrective action has been initiated.

- Despite careful clinical and roentgenologic examinations, the true sequelae of even minor spinal trauma cannot be radiographically identified or clarified immediately following ejection injury. Only after long periods of observation with systematic serial roentgenographic examinations are the secondary sequelae recognized.

- The basic orthopedic biomechanical principles employed herein to uncover the mechanics and modes of operational spinal injuries should be applied to other operational weapon systems.

APPENDIX A

ANATOMICAL REVIEW OF THE SPINAL COLUMN

To better understand the pathogeny of spinal injuries, review of basic anatomic concepts on the anatomy of the spine and its range of motion is essential. In this synopsis, only the osteology and range of motion of the spinal column are of concern.

The vertebral column of man forms the primary structural member of the musculoskeletal system. It is important for the physical status of the whole body. It supports the head, bears the ribs, and encloses the spinal cord. It gives origin to many muscles, some passing between different parts of the spine and others connecting it with other parts of the body. Its mechanical nature can be viewed as a series of segmented bony elements, each posed on a cartilaginous structure that allows adjoining segments to simultaneously possess many degrees of freedom and rigidity. Its primary, mechanical function is to couple extensional, shear, torsional, and flexural motions.

The bones comprising the spinal column are called vertebrae, of which there are 24. They are divided into three groups. The first seven are the cervical; the next twelve, which bear the ribs, are thoracic; and the remaining five are identified as the lumbar vertebrae. Below the vertebrae, seven bones are united into two structures, the first five forming the sacrum, and the remaining two, the coccyx (Figure 39). The vertebrae above the sacrum present the following features common to all, but each is slightly modified according to its functions and level within the spinal column: (1) a body or centrum, (2) pedicles, (3) the lamina, (4) spinous process, (5) transverse processes, (6) four articulating surfaces, and (7) costal elements (Figure 40). The vertebral bodies of the thoracic column are all formed on a similar architectural plan; however, their individual size, structure, and functional characteristics differ at the various thoracic levels.

From a biomechanical point of view, a typical vertebra consists of an anterior segment, mainly the centrum, and a posterior segment of the vertebral arch and its accessory processes.

The anterior segment consists of a body that is largely composed of spongy bone surrounded by a thin wall of cortical tissue and capped superiorly and inferiorly by the cartilaginous plates of the intervertebral disks. The intervertebral cartilaginous plates are directly fastened to the spicules of the vertebral centrum and peripherally abut to a raised rim of dense bone identified as the vertebral rim.

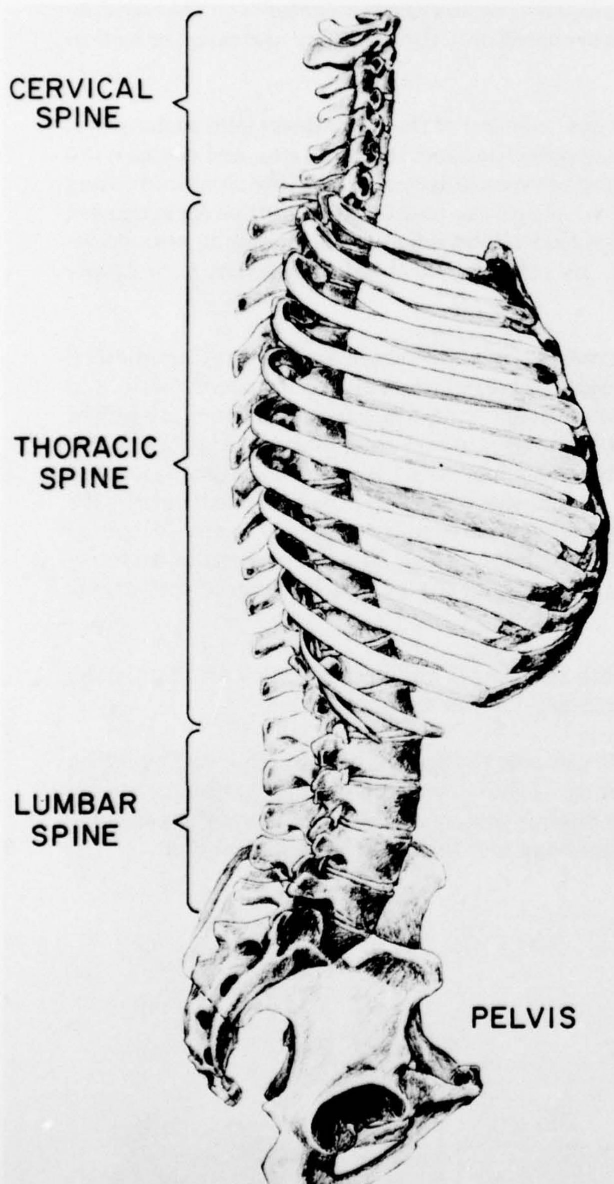


Figure 39. The Human Spinal Column and Pelvis

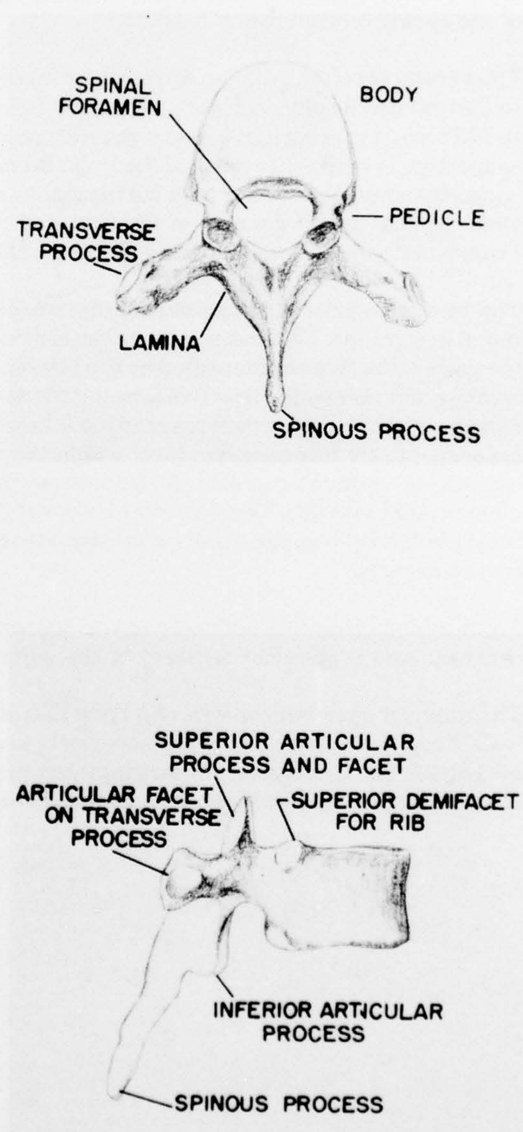


Figure 40. The Anatomy of a Thoracic Vertebra

The posterior segment is made up of the vertebral arch and its accessory processes. Each vertebral body bears paired pillared extensions identified as pedicles, which, in turn, support the laminae. The laminae and pedicles form the vertebral arch. Each vertebra carries two pairs of posterior articular processes. They are identified as superior and inferior articular processes. These paired articular processes bear smooth facets for articulation with the vertebra above and below. The spinous process permits muscular attachment. The two transverse processes serve for the attachment of the paravertebral muscles.

The anterior support of the spine is made up of vertebral bodies and the intervertebral disks. The posterior support is made up of the neural arch and the posterior vertebral articulations. The intrinsic stability of the anterior vertebral column is the result of the imbibition pressure within the intervertebral disk which tends to push the vertebral bodies apart. The posterior vertebral column resists the compressive actions of the anterior vertebral column by exerting a continual tensile force attempting to resist the compressive loading of the anterior column. The anterior spinal column is made up of spongy bone while the bony pillared articular arches form a relatively incompressible element.

When the vertebral column is viewed as a whole, marked differences are seen in its range of motion and in the action of the vertebral units. The range of motion of the human spinal column with respect to the normal upright posture and with the pelvis fixed is shown in Figure 41. Bending forward is identified as flexion, bending backward is identified as extension.

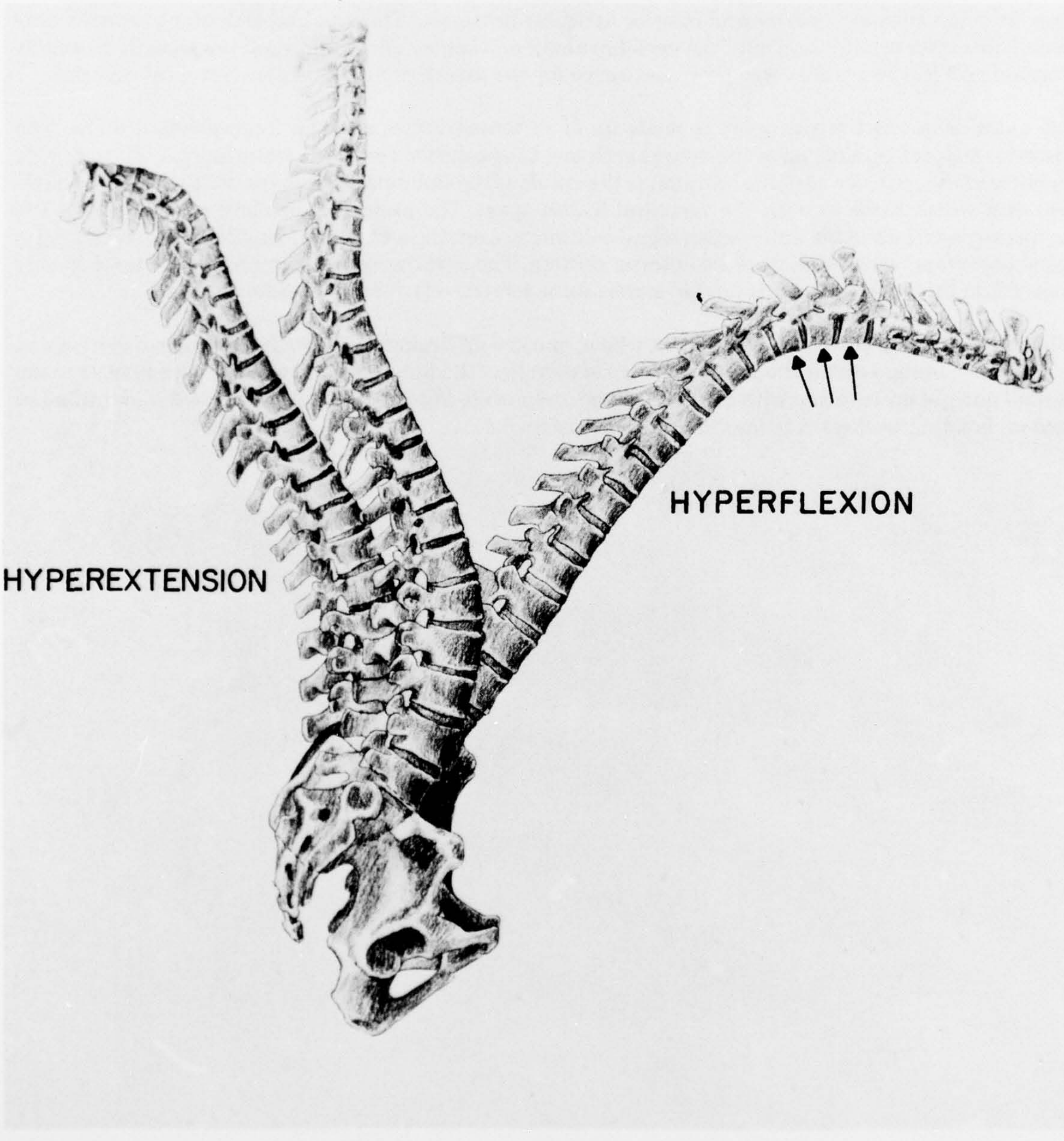


Figure 41. The Kinesiology of the Human Spine [Hyperflexion Produces Stresses on the Anterior Aspect of the Vertebral Body]

APPENDIX B

F/FB-111 CREW MODULE ESCAPE SYSTEM

The F/FB-111 Crew Escape System consists of an ejectable crew module (Figure 42) that forms an integral portion of the aircraft forward fuselage during normal flight operations and encompasses the pressurized cabin and forward portion of the wing glove. The crew module provides emergency escape and safe recovery from the aircraft at all flight altitudes and load factors within the design limit structural strengths and within the velocity altitude performance envelope of the parent aircraft.

The ejection equipment consists of the necessary severance subsystems: recovery subsystem, impact attenuation subsystem, flotation and uprighting subsystem, emergency ground escape subsystem, and survival provisions. Each crewmember is provided with an individual ejection initiator. Actuation of either crewman's ejection initiator provides an explosive impulse sequenced to lock the shoulder harness inertia reel into the retracted position, ignite the rocket motor, activate the severance components, and to deploy the stabilization brake, recovery parachutes and impact attenuation bag. The rocket motor, located between the crewmembers and behind the seat bulkhead, provides the thrust to propel the crew module up and away from the aircraft.

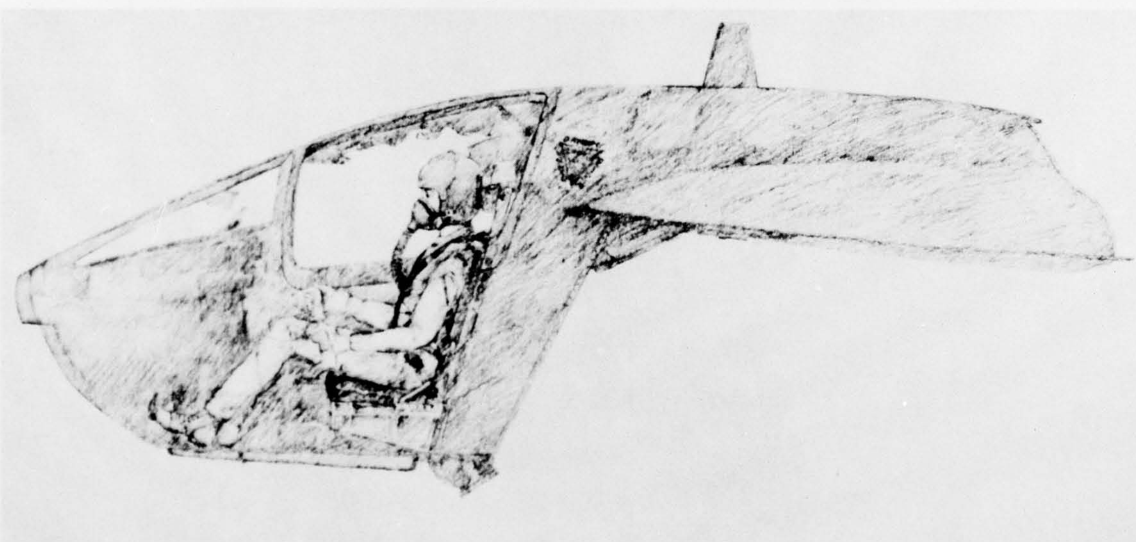


Figure 42. F/FB-111 Crew Escape Module

F/FB-111 SUPPORT AND RESTRAINT SUBSYSTEM (FIGURE 43)

The F/FB-111 seat moves up and down electrically for a total span of 5 inches, and the seat pan moves fore and aft manually through five stops, which are approximately one inch apart. As the seat pan moves forward, the angle formed by the seat back and seat pan becomes obtuse; hence, the torso of the aircrewman moves away from the vertical, and as a consequence the angle formed between the aircrewman's shoulder and the fixed inertia reel take-up decreases. On the other hand, if the seat pan is moved back, toward the vertical position, the angle formed by the aircrewman's shoulder and the place of action of the inertia reel increases. Moving the seat up increases the angle, and moving the seat down decreases the angle. The significance of this motion is related to the positioning of an aircrewman with respect to the angle of action (pull) of the powered inertia reel and the potential for hyperextension injury.

Figure 43. The Support and Restraint System Showing Position of the Inertia Reel and the Strap Anchors

The seat back of the F/FB-111 is 22.25 inches in length. The anchors for the inertia reel are mechanically set at 23.5 inches above the seat pan. An aircrewman who has a shoulder height of 23.5 inches or more is automatically sitting above the level of the inertia reel anchor points regardless of seat position. The shoulder height of the 95th, 50th, and 4th percentile crewmen are 27.3, 25.4 and 23.5 inches, respectively. The seat headrest structure is attached to the aft bulkhead, and the headrest has seven fore and aft adjustments for movement. As the headrest moves forward, the seat back pivots forward.

The RAF-IAM harness system is used in the F/FB-111. The restraint harness consists of two lap belts and two shoulder straps with an anchor (negative g) strap, which converge at the quick release box (QRB) near the crewmember's midsection. The shoulder straps rising from the QRB pass through an adjustable buckle attached to a small roller on each side. These straps are attached to a second pair of straps, which descend from the inertia reel mechanism, pass through the rollers, turn back and are fastened to the other side of the seat back cross member (the shoulder reflected straps). This double shoulder strap assembly is carried on a "horse-collar"-shaped pad. The purpose of the "horse-collar" is to provide lateral torso support; however, due to the fact that the inertia reel anchors are located below shoulder height the purpose of the "horse-collar" is defeated. The position of the inertia reel with respect to an individual's sitting height varies because the inertia reel is stationary.

F/FB-111 INERTIA REEL

Each crew seat is equipped with a powered inertia reel located behind and below the headrest. The inertia reel is positioned to accommodate a 5th through 95th percentile sitting height individual with the seat either in its full "up" or full "down" position. This reel is equipped with a two-position (automatic and manual) control handle. During normal flight, the restraining harness is unlocked and provides free body movement for the crewmember. Between 2 and 3 G, the straps will automatically lock and will not extend, although they may be retracted to any desired position. Within 0.35 second of initiation of ejection, each aircrewman is forcibly prepositioned and restrained against the back of the seat prior to module separation. The purpose of this positioning function is to insure that ejection accelerations are directed optimally to the crewmembers. Regardless of sitting posture, the inertia reel anchor points are below an aircrewman's shoulders. The backrest of the F/FB-111 seat comes up to the level of T_4-T_5-T_6. The interspace between the backrest and the headrest affords no support on powered retraction.

F/FB-111 EJECTION SEQUENCE

Once an aircrewman initiates ejection, there is a 0.35-second delay to allow for powered retraction and repositioning of the crewmember's torso, the crew module is severed, and the rocket motor ignited. Full rocket thrust is sustained for approximately 1 second. The stabilization brake parachute is deployed 0.15 second following crew module severance. This parachute provides acceleration control and stabilization at speeds above 450 knots. Recovery parachute deployment is timed by a sequencing system that senses speed, acceleration and altitude upon ejection.

At speeds below 300 knots and altitudes below 15,000 feet, the recovery parachute is deployed after a 1-second delay. At speeds above 300 knots and altitudes below 15,000 feet,recovery parachute deployment is controlled by a G-sensor initiator and is thereby delayed until crew module longitudinal (fore and aft) deceleration drops to 2.2 G. The recovery parachute is deployed upward at 45 feet per second. The initial recovery parachute inflation and the associated opening shock loads are controlled by a reefing line that holds the parachute canopy opening to about 8 feet in diameter. Parachute disreefing to full inflation occurs in 2.5 seconds after suspension line stretch. Whereas free-fall from maximum altitude to 15,000 feet occurs in 85 seconds, the remaining descent time after recovery parachute deployment is about 7.5 minutes. Landing impact is absorbed by the impact attenuation bag.

There are several possible time factors following ejection initiation wherein an aircrewman is subject to accelerative or decelerative forces during which spinal injury may occur:

(1) Once an aircrewman initiates an ejection, there is a 0.35-second delay to allow for powered repositioning of the crewmembers for "optimal" body alignment.

(2) Rocket motor ignition and thrust: A pop gun spike of about 0.025 second followed by a more sustained force on the order of 9-10 G at an airspeed of approximately 100 KIAS (as KIAS increases, G level also increases).

(3) During the first 6 inches of crew module separation, pitch flaps and stabilization (chin) flaps rotate down into deployed position; their function is to control crew module trim angle of attack.

(4) The stabilization brake parachute is deployed following crew module severance.

(5) Recovery parachute opening shock is felt.

(6) Uniform ground landing impact measures approximately 18-19 G based on a stabilized parachute descent rate of 27-29 feet/second.

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